Summary of Concrete Workability Test Methods

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16. Abstract

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This document first describes key principles and trends in the measurement of workability and then describes the 61 test methods. Based on the successes and failures of past test methods and the current needs of the concrete industry, requirements for new test methods are developed.

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SUMMARY OF CONCRETE WORKABILITY TEST METHODS

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1 INTRODUCTION

Since the early 20th century, the concrete industry has recognized the need to monitor concrete workability to ensure that concrete can be properly placed and can achieve adequate hardened strength. A myriad of test procedures for determining workability have been developed for research, mix proportioning, and field use. The vast majority of these test methods have never found any use beyond one or two initial studies. With the exception of the widely used slump test, the few methods that have been studied extensively have generally failed to gain widespread acceptance. Even with the increase in knowledge of concrete rheology, the slump test remains the predominately used test method for measuring concrete workability.

Modern concrete production systems have not eliminated the need to monitor concrete workability in the field. To the contrary, the advent of new so-called high-performance concrete mixes that are susceptible to small changes in mix proportions has made monitoring workability even more critical. Indeed, a National Ready-Mixed Concrete Association survey identified the need for a better method to characterize the workability of high performance concrete (Ferraris and Lobo 1998). After more than 80 years of efforts, the concrete industry is still faced with the challenge of developing a field test to measure the relevant rheological properties of concrete quickly and accurately.

This document describes 61 test methods for measuring concrete workability. Many more test methods have been developed for a single project or for a specific application and have been sparsely reported in the literature, if at all. Although many of the devices in this document will likely never be used in the future and have been scarcely used in the past, an examination of tests that have failed and tests that have been supplanted by better tests is instructive in recognizing trends in concrete workability research and in selecting key concepts for the development of a new test method.

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2 PRINCIPLES OF MEASUREMENT

The term workability is broadly defined; no single test method measures all aspects of workability. The American Concrete Institute (ACI 116R-00, 73) describes workability as "that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition." The Japanese Association of Concrete Engineers defines workability as "that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials" (Ferraris 1999, 464). Neville (1981, 203) succinctly defines workability as "the amount of useful internal work necessary to produce full compaction." Workability depends not just on the properties of the concrete, but

also on the nature of the application. A very dry concrete mixture may seem to have very low workability when it is, in fact, appropriate for the given application.

The focus of workability measurement has changed many times over the years. When the slump test was developed in the early 20th century, concrete researchers were just beginning to recognize the importance of water content in predicting concrete strength (Wig 1912; Abrams 1922). The slump test gives an indication of the water content, and thus the hardened strength of concrete. The ability to improve strength by controlling concrete consistency represented a new advance for the concrete industry. The slump test was quickly adopted because of its simplicity (Abrams 1922). Still, the concrete industry quickly realized the slump test's inability to represent workability fully and, within several years of the introduction of the slump test, several attempts were made to develop better, more complete tests (Powers 1968). Although numerous test methods have been developed since the 1920s, not until research established concrete as a Bingham fluid did the principle of measuring concrete flow curves in terms of shear stress and shear rate emerge (Tattersall and Banfill 1983). Many of new test methods developed since the establishment of concrete as a Bingham fluid have attempted to measure yield stress and plastic viscosity.

The multitude of workability test methods can be divided into categories based on several different classification schemes. Tattersall (1991) broadly splits the assessment of workability into three classes, as shown in Table 1. The majority of workability test methods fall into Class II and Class III.

Table 1: Classes of Workability Measurement (Tattersall 1991)

Class I Qualitative Workability, Flowability, Compactability, Finishability, Pumpability, etc.	To be used only in a general descriptive way without any attempt to quantify
Class II Quantitative Empirical Slump, Compacting Factor, Vebe Time, Flow Table Spread, etc.	To be used as a simple quantitative statement of behavior in a particular set of circumstances
Class III Quantitative Fundamental Viscosity, Mobility, Fluidity, Yield Value, etc.	To be used strictly in conformity with standard definitions

Similar to Tattersall's scheme, most test methods for workability have traditionally been split between single-point tests and multi-point tests. The concept of single-point tests versus multi-point tests is based on the flow curve relating shear stress and shear rate. A single-point test measures only one point on the flow curve and, therefore, provides an incomplete description of workability. For instance, the slump test only provides one point on the flow curve, namely, the yield stress. Multi-point tests, by contrast, measure additional points on the flow curve, typically by varying the shear rate, in order to provide a more complete description of concrete rheology. Single-point tests generally fall into Class II of Tattersall's scheme, whereas multi-point tests fall into Class III. Single-point tests can provide a direct or indirect measurement of yield stress, plastic viscosity, or some other property. Multi-point tests typically measure yield stress and

plastic viscosity, or closely related values. The existing test methods for concrete described in this document can be split between single-point and multi-point tests, as shown in Table 2.

Single-point workability tests are generally intended to be simple and rapid; however, they do not provide information on both yield stress and plastic viscosity. In some cases, a single-point test may be appropriate for a certain type of concrete mix or a certain application even though the test does not fully measure fundamental rheological parameters. The tradeoff between single-point tests and multi-point tests is generally that single-point tests are simpler yet less complete.

Table 2: Single-Point and Multi-Point Workability Tests for Concrete

Single-Point Tests		Multi-Point Tests
-- Angles Flow Box Test	-- Moving Sphere Viscometer	-- Bertta Apparatus
-- Compaction Factor Test	-- Powers Remolding Test	-- BML Viscometer
-- Compaction Test	-- Proctor Test	-- BTRHEOM Rheometer
-- Cone Penetration Test	-- Ring Penetration Test	-- CEMAGREF-IMG
-- Delivery-Chute Depth Meter	-- Settlement Column	-- FHPCM
-- Delivery-Chute Torque Meter	Segregation Test	-- IBB Rheometer
-- Flow Table Test (DIN)	-- Slump Test	-- Modified Slump Test
-- Flow Trough Test	-- Soil Direct Shear Test	-- Multiple Single-Point Tests
-- Free Orifice (Orimet) Test	-- Soil Triaxial Test	-- Powers and Wiler Plastometer
-- Fresh Concrete Tester 101	-- Surface Settlement Test	-- SLump Rate Machine (SLRM)
-- Intensive Compaction Test	-- Thaulow Tester	-- System and Method for
-- Inverted Slump Cone Test	-- Trowel Test	Controlling Concrete
-- K-Slump Tester	-- Vebe Consistometer	Production
-- Kango Hammer Test	-- Vibratory Flow Meter	-- Tattersall Two-Point Device
-- Kelly Ball Test	-- Vibropenetrator	-- Vertical Pipe Apparatus
-- LCL Flow Test	-- Wigmore Consistometer	-- Vibrating Slope Apparatus
-- Mixer Devices		

A distinction can also be made between dynamic tests and static tests. In dynamic tests, energy is imparted into the concrete through such actions as vibrating, jolting, or applying a shear force to the concrete. In contrast, static tests do not add such energy and often rely on the concrete to flow under its own weight. Dynamic tests are particularly appropriate for low and moderate workability concretes that are commonly vibrated in the field and for highly thixotropic concretes where energy is required to overcome the initially high at-rest yield stress.

Workability test methods have also been classified in terms of the type of flow produced during the test. In an effort to establish a uniform and widely accepted nomenclature for concrete rheology, the National Institute of Standards and Technology (NIST) divided existing rheology test methods into four broad categories (Hackley and Ferraris 2001). The definitions of the four categories are listed in Table 3.

Table 3: NIST Categorization of Concrete Rheology Test Methods
(Hackley and Ferraris 2001)

Category	Definition
Confined Flow Tests	The material flows under its own weight or under an applied pressure through a narrow orifice.
Free Flow Tests	The material either flows under its own weight, without any confinement or an object penetrates the material by gravitational settling.
Vibration Tests	The material flows under the influence of applied vibration. The vibration is applied by using a vibrating table, dropping the base supporting the material, an external vibrator, or an internal vibrator.
Rotational Rheometers	The material is sheared between two parallel surfaces, one or both of which are rotating.

The NIST classification scheme is most consistent with the current understanding of concrete rheology and workability. Confined flow, free flow, and vibration test methods generally attempt to simulate field placement flow conditions, whereas rotational rheometers attempt to apply the concepts of traditional rheometers to concrete. It must be recognized that some existing test methods—such as many of the tests for low-slump concrete—do not directly measure the flow properties of concrete and, therefore, do not fit into any of the above four categories. The results of these tests can still give meaningful information on concrete workability.

3   DESCRIPTIONS OF EXISTING TEST METHODS

The 61 workability test methods described in this document are presented in accordance with the NIST flow-type classification scheme. Since concrete, paste and grout, and self-compacting concrete are each rheologically unique, test methods for each material can be divided into separate categories, as shown in Table 4. Some test methods that do not fit into any of the four NIST flow-type categories are described in separate categories.

Table 4: Categorization of Concrete Workability Test Methods

Tests for Concrete		Tests for Self Compacting Concrete	Tests for Pastes and Mortars
>*Confined Flow Tests* -- Compaction Factor Test -- Free Orifice (Orimet) Test -- K-Slump Tester >*Free Flow Tests* -- Cone Penetration Test -- Delivery-Chute Depth Meter -- Delivery-Chute Torque Meter -- Flow Trough Test -- Kelly Ball Test -- Modified Slump Test -- Moving Sphere Viscometer -- Ring Penetration Test -- SLump Rate Machine (SLRM) -- Slump Test -- Surface Settlement Test >*Vibration Tests* -- Angles Flow Box Test -- Compaction Test -- Flow Table Test (DIN) -- Inverted Slump Cone Test -- LCL Flow Test -- Powers Remolding Test -- Settlement Column Segergation Test -- Thaulow Tester -- Vebe Consistometer -- Vertical Pipe Apparatus -- Vibrating Slope Apparatus -- Vibropenetrator -- Wigmore Consistometer -- Vibratory Flow Meter	>*Rotational Rheometers* -- Bertta Apparatus -- BML Viscometer -- BTRHEOM Rheometer -- CEMAGREF-IMG -- FHPCM -- Fresh Concrete Tester 101 -- IBB Rheometer -- Mixer Devices -- Powers and Wiler Plastometer -- Soil Direct Shear Test -- Tattersall Two-Point Device >*Tests for Very Low Workability Concrete* -- Intensive Compaction Test -- Kango Hammer Test -- Proctor Test >*Other Test Methods* -- Multiple Single-Point Tests -- Soil Triaxial Test -- System and Method for Controlling Concrete Production -- Trowel Test	>*Confined Flow Tests* -- Fill-Box Test -- L-Box Test -- U-Box Test -- V-Funnel Test >*Free Flow Tests* -- J-Ring Test -- Slump Flow Test >*Stability Tests* -- Penetration Test for Segregation -- Wet Sieving Stability Test	-- Flow Cone Test -- Miniflow Test -- Minislump Test -- Turning Tube Viscometer -- Vicat Needle Test -- ViscoCorder -- Wuerpel Device

Each category of test methods is described in general terms in the sections that follow. After the general description of each category, the test methods are described and critiqued.

3.1 Workability Test Methods for Concrete

The workability test methods for concrete presented in this document cover a broad range of workability, from extremely dry roller-compacted concrete to highly flowable mixtures. The test methods range from simple tests that can be performed in less than a minute to more complex tests that require expensive equipment and knowledgeable operators. Although some of the tests

are appropriate for only a narrow range of concrete mixtures, such tests can still provide highly useful information. The following subsections describe the workability test methods for concrete and summarize the key advantages and disadvantages of each test method.

3.1.1 Confined Flow Test Methods

Only three confined flow tests methods for concrete are presented in this document. However, the use of confined flow in measuring workability is much more extensive than this short list suggests. Many of the tests available for self-compacting concrete are confined flow tests. Generally confined flow tests are not suitable for low to moderate slump concretes, which are not sufficiently fluid to readily flow under confined conditions and produce meaningful test results. Since vibration imparts energy into concrete and produces flow in low to moderate slump concretes, some vibration tests feature confined flow. Such tests that incorporate both vibration and confined flow—including the inverted slump cone test and the vertical pipe apparatus—are classified as vibration tests.

The three confined flow tests presented in this document are simple to perform and provide additional information that the slump test does not provide. However, the tests are more complex than the slump test—though much less complex than rotational rheometers—and are not widely used.

3.1.1.1 Compaction Factor Test (Compacting Factor Test, Glanville Compaction Test)

The compaction factor test (Powers 1968; Neville 1981; Bartos 1992; Bartos, Sonebi, and Tamimi 2002) measures the degree of compaction resulting from the application of a standard amount of work. The test was developed in Britain in the late 1940s and has been standardized as British Standard 1881-103.

The apparatus, which is commercially available, consist of a rigid frame that supports two conical hoppers vertically aligned above each other and mounted above a cylinder, as shown in Figure 1. The top hopper is slightly larger than the bottom hopper, while the cylinder is smaller in volume than both hoppers. To perform the test, the top hopper is filled with concrete but not compacted. The door on the bottom of the top hopper is opened and the concrete is allowed to drop into the lower hopper. Once all of the concrete has fallen from the top hopper, the door on the lower hopper is opened to allow the concrete to fall to the bottom cylinder. A tamping rod can be used to force especially cohesive concretes through the hoppers. The excess concrete is carefully struck off the top of the cylinder and the mass of the concrete in the cylinder is recorded. This mass is compared to the mass of fully compacted concrete in the same cylinder achieved with hand rodding or vibration. The compaction factor is defined as the ratio of the mass of the concrete compacted in the compaction factor apparatus to the mass of the fully compacted concrete. The standard test apparatus, described above, is appropriate for maximum aggregate sizes of up to 20 mm. A larger apparatus is available for concretes with maximum aggregate sizes of up to 40 mm.
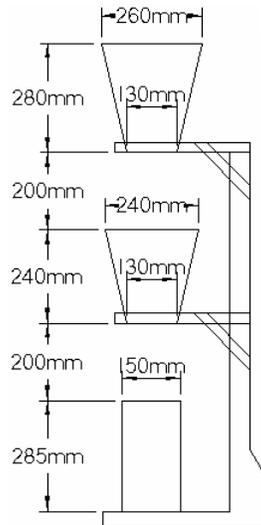
Figure 1: Compaction Factor Test Apparatus

The results of the compaction factor test can be correlated to slump, although the relationship is not linear. Table 5 relates the results of the compaction factor test to slump and the sample's degree of workability.

Table 5: Interpretation of Compaction Factor Test Results as Described in British Road Note 4 (Wilby 1991)

Degree of Workability	Slump, mm	Compaction Factor		Applications
		Small Apparatus	Large Apparatus	
Very Low	0-25	0.78	0.80	Vibrated concrete in roads or other large sections.
Low	25-50	0.85	0.87	Mass concrete foundations without vibration. Simple reinforced sections with vibration.
Medium	50-100	0.92	0.935	Normal reinforced work without vibration and heavily reinforced sections with vibration.
High	100-180	0.95	0.96	Sections with congested reinforcement. Not normally suitable for vibration.

The compaction factor test has been used more widely in Europe than in the United States, although the overall use of the test seems to be declining. The test has typically been used in precast operations and at large construction sites. Compared to the slump test, the apparatus is bulky and a balance is required to perform measurements. In addition to these practical drawbacks, the test has several flaws that reduce the accuracy of the results. Some of the work imparted into the concrete is lost in friction between the hoppers and the concrete. The magnitude of this friction varies between different concrete mixtures and may not reflect field

conditions. Further, the compaction factor test does not utilize vibration, the main compaction method used in the field (Bartos 1992).

Advantages:
- The compaction factor test gives more information (that is, about compactability) than the slump test.
- The test is a dynamic test and thus is more appropriate than static tests for highly thixotropic concrete mixtures.

Disadvantages:
- The large and bulky nature of the device reduces its usefulness in the field. Further, the test method requires a balance to measure the mass of the concrete in the cylinder.
- The amount of work applied to the concrete being tested is a function of the friction between the concrete and the hoppers, which may not reflect field conditions.
- The test method does not use vibration, the main compaction method used in the field.
- Although the test is commercially available, it is used infrequently.

3.1.1.2 Free Orifice Test (Orimet Test)

The free orifice test (Bartos 1992; Bartos 1994; Wong et al. 2000; Bartos, Sonebi, and Tamimi 2002) measures the time for concrete to flow through a vertical tube and out a smaller diameter orifice at the bottom of the tube. The test was originally developed by Bartos in 1978 as a rapid field test to measure the workability of concretes that were too flowable to be measured with the slump test.

The apparatus consists of a 600 mm long, 100 mm diameter pipe held in a vertical position with a tripod. An interchangeable orifice, which narrows the diameter of the pipe, is attached to the bottom of the pipe. The standard orifice size of 80 mm is appropriate for concrete mixes with a maximum aggregate size of 20 mm. Other typical orifice sizes are 70 mm and 90 mm. To perform the test, concrete is placed in the pipe but not compacted. A door on the bottom of the orifice is opened and the time for the concrete to flow completely out of the pipe is measured. For normal, flowable concrete mixes, Bartos (1992) reported typical flow times of 1.5 to 6 seconds; however, more cohesive concretes can have flow times greater than 60 seconds. If a mix is highly susceptible to segregation, coarse aggregates tend to accumulate near the orifice and slow or completely block flow. A non-continuous discharge can suggest a concrete mixture's susceptibility to segregation. The standard test requires approximately 7.5 liters of concrete and should be repeated at least 2-3 times. In some cases, the results of the free orifice test have been correlated to slump (Wong et al. 2000).

The free orifice test is simple and easily portable; however, it requires modifications in order to measure a wider range of concrete mixtures. For concretes with low slump, a vibrator could be attached externally to the pipe in order to promote flow. Different size aggregates require different size orifices, a fact that complicates the comparison of test data. The main source of error is operator error in measuring the exact start and stop times for the test.

Wong et al. (2000) made several recommendations for modifying the free orifice device in order to obtain additional information about the concrete mix. The time for the concrete to flow out of

the tube could be used in addition to slump in order to characterize workability better. Alternatively, multiple shear rates could be achieved by placing surcharge weights on the concrete. While this idea of using multiple shear rates has been suggested, it is unknown whether this idea has been attempted.

In a test of anti-washout mixtures conducted by Bartos (1994), the free orifice device clearly showed changes in the cohesiveness of the concrete mixtures. Further, the free orifice test successfully showed sensitivity to changes in fine aggregate content. By contrast, when the flow table test was performed on the same concrete mixtures, the associated changes in workability due to changes in fine aggregate content were not detected.

Advantages:
- The test is inexpensive and simple to use. Even if the apparatus is not placed on level ground, an accurate result can still be obtained.
- The test quickly provides a direct result.
- The test represents a good simulation of actual placing conditions for highly flowable concretes.

Disadvantages:
- The test method is only appropriate for highly flowable and self-compacting concretes.
- Although the test provides a good indication of cohesiveness, the results are not expressed in terms of fundamental units.

3.1.1.3 K-Slump Tester

The K-slump tester (Bartos 1992; Scanlon 1994; Ferraris 1999; Wong et al. 2000; US patent 3,863,494; Bartos, Sonebi, and Tamimi 2002) is a small device that can be inserted directly into a mass of fresh concrete to determine slump quickly. The test was developed by K.W. Nasser in the 1970s and is sometimes referred to as the "Nasser probe."

The device consists of a hollow tube with slots and holes, as shown in Figure 2. The end with the pointed tip is inserted in the concrete. A flat plate at approximately mid-height of the tube indicates the proper depth of penetration of the device. A round plunger moves freely out the other end. The tube is inserted into the concrete with the plunger in the upper position to allow mortar from the concrete to enter the inside of the tube. After 60 seconds the plunger is lowered until it comes to rest on top of the mortar that has entered the tube. The depth of mortar in the tube, as read from the graduated scale on the plunger is taken as the K-slump. The plunger is again pulled to its upper position and the tube is removed from the concrete. After mortar is allowed to flow out of the tube, the plunger is lowered to rest on top of the remaining mortar in the tube. The reading on the graduated scale at this point is considered the workability, W.

The K-slump reading is linearly related to slump. The higher the workability reading, W, the greater is the workability and compactability of the mix. The difference between K and W is an indication of the susceptibility of a mixture to segregation.
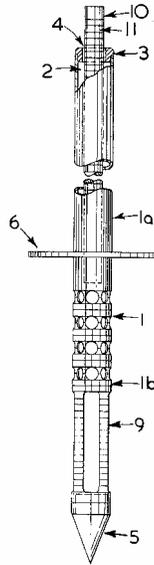
Figure 2: K-Slump Tester (US Patent 3,863,494)

The K-slump tester was standardized as ASTM C1362 in 1997 and is commercially available. A digital version of the tester has also been developed (US patent 5,437,181). The device is appropriate for medium and high workability concretes. The test cannot be modeled analytically and does not directly measure plastic viscosity, although the K and W terms provide greater information than just the slump. Since aggregates greater in size than the 3/8 inch slots cannot fit into the tube, the test does not fully measure the influence of aggregate on workability. Indeed, the scatter of the test results is large (Ferraris 1999).

Advantages:
- The K-slump tester is simple and easier to use than the slump test. A direct result is available in approximately one minute.
- The test can be performed on in-situ concrete.
- The K and W terms provide more information than just the slump.

Disadvantages:
- The test does not fully take into account the effects of coarse aggregates.
- The test is static and is not appropriate for low slump concrete mixtures.

3.1.2 Free Flow Test Methods

Free flow test methods are generally simple to perform and provide a clear, direct result. The slump test is the best known of the free flow test methods. Other free flow test methods represent attempts to improve on the slump test. Free flow tests generally give a result that is closely related to yield stress. A few tests have been improved to measure plastic viscosity also. Although many of the free flow tests can be used on concretes with a wide range of workability, none of the free flow tests features vibration. Tests that do not include vibration may not be the

most appropriate test methods for characterizing low workability and highly thixotropic concrete mixtures.

3.1.2.1 Slump Test

The slump test is the most well-known and widely used test method to characterize the workability of fresh concrete. The inexpensive test, which measures consistency, is used on job sites to determine rapidly whether a concrete batch should be accepted or rejected. The test method is widely standardized throughout the world, including in ASTM C143 in the United States and EN 12350-2 in Europe.

The apparatus consists of a mold in the shape of a frustum of a cone with a base diameter of 8 inches, a top diameter of 4 inches, and a height of 12 inches. The mold is filled with concrete in three layers of equal volume. Each layer is compacted with 25 strokes of a tamping rod. The slump cone mold is lifted vertically upward and the change in height of the concrete is measured. Four types of slumps are commonly encountered, as shown in Figure 3. The only type of slump permissible under ASTM C143 is frequently referred to as the "true" slump, where the concrete remains intact and retains a symmetric shape. A zero slump and a collapsed slump are both outside the range of workability that can be measured with the slump test. Specifically, ASTM C143 advises caution in interpreting test results less than ½ inch and greater than 9 inches. If part of the concrete shears from the mass, the test must be repeated with a different sample of concrete. A concrete that exhibits a shear slump in a second test is not sufficiently cohesive and should be rejected.

| True | Zero | Collapsed | Shear |
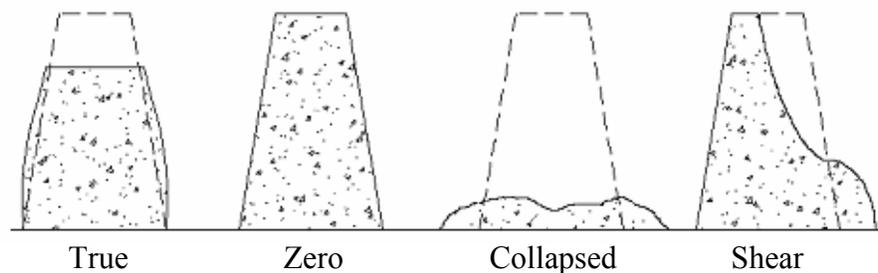
Figure 3: Four Types of Slump

The slump test is not considered applicable for concretes with a maximum coarse aggregate size greater than 1.5 inches. For concrete with aggregate greater than 1.5 inches in size, such larger particles can be removed by wet sieving.

Additional qualitative information on the mobility of fresh concrete can be obtained after reading the slump measurement. Concretes with the same slump can exhibit different behavior when tapped with a tamping rod. A harsh concrete with few fines will tend to fall apart when tapped and be appropriate only for applications such as pavements or mass concrete. Alternatively, the concrete may be very cohesive when tapped, and thus be suitable for difficult placement conditions.

Slump is influenced by both yield stress and plastic viscosity; however, for most cases the effect of plastic viscosity on slump is negligible. Equations have been developed for calculating yield stress in terms of slump, based on either analytical or experimental analyses. Since different rheometers measure different absolute values for the yield stress of identical samples of concrete, the experimental equations are largely depended on the specific device used to measure yield stress.

Based on a finite element model of a slump test, Hu et al. (1996) developed an expression for yield stress in terms of slump and density, as shown in Equation [1]. The finite element calculations were performed for concretes with slumps ranging from zero to 25 cm. The equation is not appropriate for concretes with a plastic viscosity greater than 300 Pa.s, above which viscosity sufficiently slows flow and causes thixotropy, resulting in a reduction of the actual slump value. An experimental study to verify the results of the finite element model showed "satisfactory" agreement between Equation [1] and yield stress measurements from the BTRHEOM rheometer. It should be noted that the finite element calculations were preformed for concrete with slumps as low as zero, while the BTRHEOM rheometer can only measure concretes with slumps greater than approximately 10 cm.

$$\tau_0 = \frac{\rho}{270}(300 - s) \qquad\qquad [1]$$

where τ_0 = yield stress in Pa, s = slump in mm, and ρ = density in kg/m^3.

Based on additional experimental measurements with the BTRHEOM rheometer, Ferraris and de Larrard (1998) altered Equation [1], as shown in Equation [2]:

$$\tau_0 = \frac{\rho}{347}(300 - s) + 212 \qquad\qquad [2]$$

Murata and Kikukawa (1992) used a coaxial cylinders rheometer to develop an empirical equation for yield stress in terms of slump for concretes with slumps ranging from 12.5 cm to 26 cm, as shown in Equation [3]:

$$\tau_0 = 714 - 473\log(s) \qquad\qquad [3]$$

where τ_0 = yield stress in Pa and s = slump in cm.

A comparison of the equations developed by Hu et al. (1996), Ferraris and de Larrad (1998), and Murata and Kikukawa (1992) is presented in Figure 4.
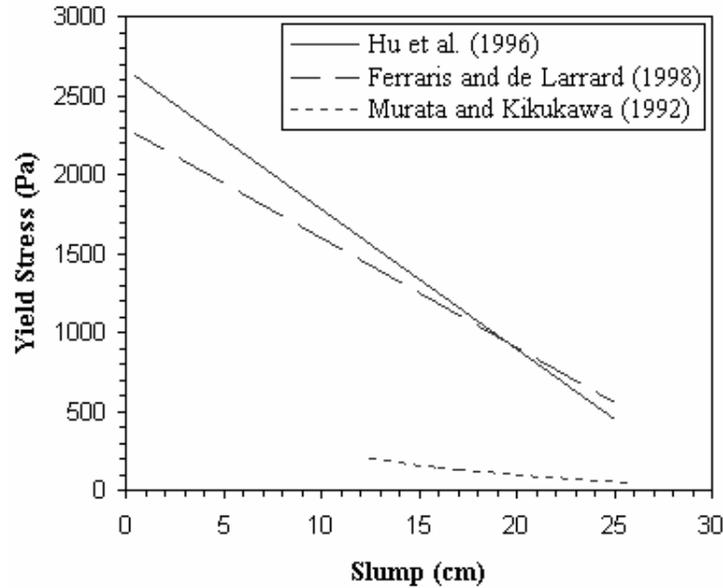
Figure 4: Comparison of Equations Relating Yield Stress to Slump

Using a viscoplastic finite element model, Tanigawa and Mori (1989) developed three-dimensional graphs relating slump, yield stress, and plastic viscosity for concretes with slumps ranging from 1 to 26 cm. Schowalter and Christensen (1998) developed a simple analytical equation to relate slump to yield stress and the height of the unyielded region of the slump cone, defined as the region where the weight of concrete above a given point is insufficient to overcome the yield stress. Other, more complex analytical analyses have been developed. Additionally, Tattersall and Banfill (1983) have presented experimental data showing a relationship between slump and yield stress.

Advantages:
- The slump test is the most widely used device worldwide. In fact, the test is so well known that often the terms workability and slump are used interchangeably, even though they have different meanings.
- Specifications are typically written in terms of slump.
- The slump test is simple, rugged, and inexpensive to perform. Results are obtained immediately.
- The results of the slump test can be converted to yield stress in fundamental units based on various analytical treatments and experimental studies of the slump test.
- Compared to other commonly used concrete tests, such as for air content and compressive strength, the slump test provides acceptable precision.

Disadvantages:
- The slump test does not give an indication of plastic viscosity.
- The slump test is a static, not dynamic, test; therefore, results are influenced by concrete thixotropy. The test does not provide an indication of the ease with which concrete can be moved under dynamic placing conditions, such as vibration.
- The slump test is less relevant for newer advanced concrete mixes than for more conventional mixes.

3.1.2.2 Modified Slump Test

The modified slump test (Ferraris and de Larrard 1998; Ferraris 1999; Ferraris and Brower 2001) is intended for use as a field test to measure both the plastic viscosity and yield stress of concrete mixtures. The test adds the parameter of time to the standard slump test in order to measure plastic viscosity.

The apparatus for the modified slump test consists of a vertical rod that extends from a horizontal base plate through the center of the standard slump cone. The slump cone is filled in accordance with ASTM C143 and a sliding disk is placed atop the fresh concrete. Once the slump cone is removed, the time for the disk to slide a distance of 100 mm is measured. The sliding disk comes to rest on a stop located on the vertical rod. After the disk comes to rest, the concrete continues to subside to its final position. The final slump measurement is recorded no later than 60 seconds after the slump cone is removed. A schematic of the test procedure is shown in Figure 5.
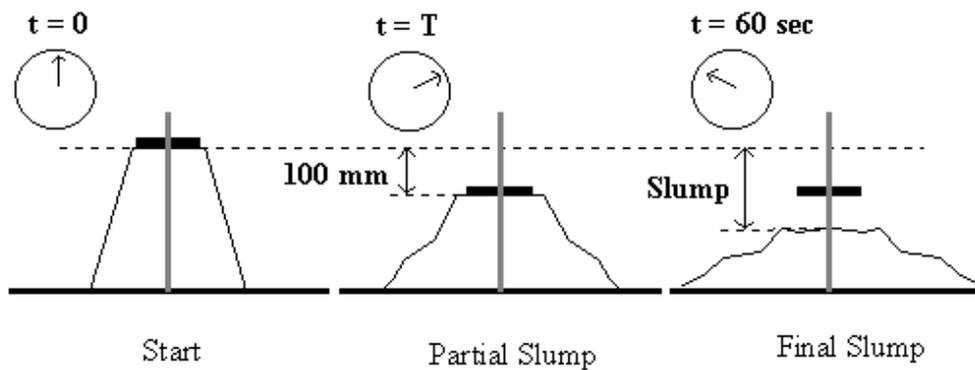
Figure 5: Schematic of the Modified Slump Test (Ferraris and de Larrard 1998)

The rheological parameters of yield stress and plastic viscosity can be expressed in fundamental units using equations based on the results of the test. The yield stress (τ_0, Pa) is expressed in terms of final slump (s, mm) and concrete density (ρ, kg/m^3); while the plastic viscosity (μ, Pa.s) is a function of final slump, slump time (T, sec), and concrete density. The proposed expression for yield stress is the modified form of Equation [1], given previously as Equation [2] and repeated below:

$$\tau_0 = \frac{\rho}{347}(300 - s) + 212$$

The equation for plastic viscosity is based on a semi-empirical model developed by using the results of the modified slump test, as shown in Equation [4]:

$$\text{For 200 mm} < s < 260 \text{ mm:} \quad \mu = \rho T \cdot 1.08 \cdot 10^{-3} (s - 175)$$
$$\text{For } s < 200 \text{ mm:} \quad \mu = 25 \cdot 10^{-3} \rho T \tag{4}$$

Nomographs have been developed based on the above equations to allow quick determination of yield stress and plastic viscosity in the field.

Due to the need to measure the time for a slump of 100 mm to be achieved, the test only applies to concrete with slumps ranging from 120 to 260 mm. It has been shown that the rod has a negligible effect on the final slump and that there is no risk of the concrete falling faster than the plate. Other researchers have eliminated the sliding plate and shortened the rod so that it terminates 100 mm below the top of the slump cone (Ferraris 1999). There is a possibility of operator error in determining the precise instances to start and stop the measurement of the slump time.

Additional experimental testing needs to be carried out on a wider range of concrete mixtures in order to verify the validity of the test. Ferraris and Brower (2001) found poor correlation between the results of the modified slump test and plastic viscosity measured with five rotational rheometers.

Advantages:
- The test is simple to conduct and only requires slightly more equipment than the slump test.
- The test gives an indication of both yield stress and plastic viscosity.

Disadvantages:
- The test is not a dynamic test and does not account for the thixotropy of concrete or the ability of concrete to flow under vibration.
- Further testing is required to verify the validity of the test.

3.1.2.3 SLump Rate Machine (SLRM)

Like the modified slump test, the SLump Rate Machine (SLRM) introduces the variable of time to the standard slump test in order to obtain more information about concrete rheology (Chidiac et al. 2000).

The test is based on an analytical treatment of the slump test. It can be shown analytically that the yield stress of concrete is a function of concrete density, ρ, and the horizontal slump flow of the concrete, *Sf*, as shown in Equation [5]:

$$\tau_y = \frac{4gV}{\pi\sqrt{3}} \frac{\rho}{(Sf)^2} = \beta_1 \frac{\rho}{(Sf)^2} \tag{5}$$

where g = gravity and V = volume of the slump cone.

Further, it can be shown that plastic viscosity is a function of horizontal slump flow; slump, sl; and time of slump, t_{slump}, as shown in Equation [6]:

$$\eta = \frac{gHV\rho}{150\pi(Sl)(Sf)^2}t_{slump} = \beta_2 \frac{\rho}{(Sl)(Sf)^2}t_{slump} = \frac{\beta_2}{\beta_1}\frac{\tau_y}{(Sl)}t_{slump} \qquad [6]$$

where H = height of slump cone mold.

Based on the above two equations, the fundamental rheological constants can be determined by measuring slump, slump flow, and slump time. The SLRM is a computer-controlled device that measures these three variables. After the slump cone is manually filled, a motor lifts the slump cone at a constant rate in compliance with ASTM C143. A plate rests on top of the concrete cone and is attached to a displacement transducer to record slump versus time. The device must be calibrated to take into account the friction between the concrete and the slump cone and the effect of the weight of the rod and plate attached to the displacement transducer.

Tests were conducted on multiple concrete mixes with a wide range of workability in order to judge the validity of the test device. Equation [5] for yield stress and Equation [6] for plastic viscosity represented the experimental data well and provided results that were generally consistent with other experimental and analytical equations.

Advantages:
- The test gives an indication of both yield stress and plastic viscosity.
- The test is simpler and less expensive than traditional rheometers; however, it does provide less information about the concrete.

Disadvantages:
- The test is not a dynamic test and does not account for the thixotropy of concrete nor does it measure the ability of concrete to flow under vibration.
- The test device is more complicated than the modified slump test and requires the use of a computer to log data and perform calculations.
- Further testing is required to verify the validity of the test.

3.1.2.4 Kelly Ball Test

The Kelly ball test (Powers 1968; Bartos 1992; Scanlon 1994; Ferraris 1999; Bartos, Sonebi, and Tamimi 2002) was developed in the 1950s in the United States as a fast alternative to the slump test. The simple and inexpensive test can be quickly performed on in-place concrete and the results can be correlated to slump.

The test apparatus consists of a 6 inch diameter, 30 pound ball attached to a stem, as shown in Figure 6. The stem, which is graduated in ¼ inch increments, slides through a frame that rests on the fresh concrete. To perform the test, the concrete to be tested is stuck off level. The ball is released and the depth of penetration is measured to the nearest ¼ inch. At least three measurements must be made for each sample.
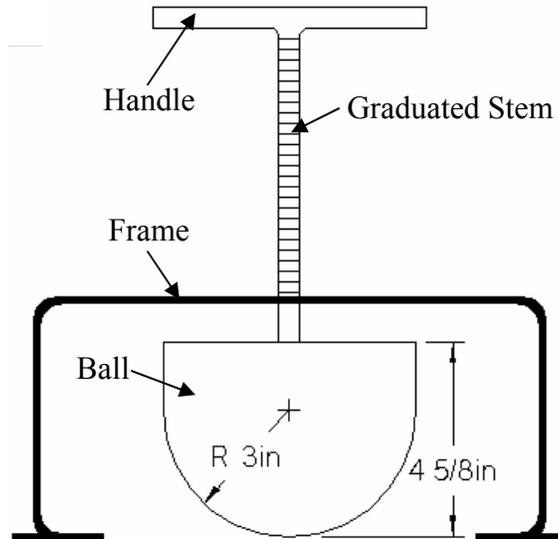
Figure 6: Kelly Ball Test Apparatus

The Kelly ball test provides an indication of yield stress, as the test essentially measures whether the stress applied by the weight of the ball is greater than the yield stress of the concrete (Ferraris 1999). For a given concrete mixture, the results of the Kelly ball test can be correlated to slump. Equations based on empirical testing have been published for use on specific types of concrete mixtures (Powers 1968). Typically, the value of slump is 1.10 to 2.00 times the Kelly ball test reading. It has been claimed that the Kelly ball test is more accurate in determining consistency than the slump test (Scanlon 1994).

The Kelly ball test was formerly standardized in ASTM C360-92: "Standard Test Method for Ball Penetration in Freshly Mixed Hydraulic Cement Concrete." The ASTM standard was discontinued in 1999 due to lack of use. The test has never been used widely outside the United States (Bartos 1992).

The test is applicable to a similar range of concrete consistencies as the slump test and is applicable to special mixes, such as lightweight and heavyweight concretes. The precision of the test declines with the increasing size of coarse aggregate (Bartos 1992).

Advantages:
- The test is faster than the slump test and can be preformed on in-place concrete to obtain a direct result quickly.
- It has been claimed that the Kelly ball test provides more accurate results than the slump test.

Disadvantages:
- Like the slump test, the Kelly ball test is a static test.
- The test must be performed on a level concrete surface.
- The test is no longer widely used.
- Large aggregate can influence the results.

3.1.2.5   Ring Penetration Test

The ring penetration test (Wong et al. 2000) consists of a steel ring that is allowed to sink under its own weight into a sample of fresh concrete. To perform the test, mass can be gradually added to the ring until the ring begins to settle into the concrete. The total mass on the ring when the ring begins to penetrate the concrete is related to yield stress. The rate at which the ring settles when a constant mass is present on the ring can also be measured. The method is considered appropriate for grouts and high-workability concretes.

Advantages:
- The ring penetration test is simple and inexpensive to perform.
- The test can be performed on in-place concrete.

Disadvantages:
- The test is only considered appropriate for grouts and highly workable concretes.
- The test is a static test that must be performed on a level concrete surface.
- Large coarse aggregate particles could interfere with the descent of the ring and distort test results.
- The test is not widely used and the interpretation of the test results is not well known.

3.1.2.6   Cone Penetration Test

The cone penetration test (Sachan and Kameswara Rao 1998) was developed to be a superior test for measuring the workability of fiber-reinforced concrete. It was designed to be an improvement over the slump test, inverted slump cone test, and Vebe consistometer.

The test apparatus consists of a 4 kg metal cone with a 30 degree apex angle. The cone is allowed to penetrate a sample of concrete under its own weight. The depth of penetration is measured as an indication of workability.

In developing the test, multiple apex angles and cone weights were examined in order to determine the optimum device characteristics. By varying the weight and apex angle, the developers of the test were able to determine a relationship between the cone weight, cone geometry, the penetration depth, and the properties of the concrete, as shown in Equation [7]:

$$d = \frac{KW^n}{\theta} \tag{7}$$

where W = cone weight, θ = apex angle, d = depth of penetration, and K and n are empirical constants based on the workability of the mix.

Sachan and Kameswara Rao found that the results of the cone penetration test correlate well to slump, inverted slump cone time, and Vebe time. The test method is suitable for low slump concrete mixes.

Unlike the inverted slump cone test and Vebe consistometer, the cone penetration is not a dynamic test and, therefore, is affected by thixotropy. Since fiber-reinforced concretes can be

highly thixotropic, the test is only appropriate for a limited range of fiber-reinforced concrete mixtures. The test method is not widely used.

Advantages:
- The test is simple to perform and provides a direct result.
- The test can be performed on in-place concrete.

Disadvantages:
- The test is a static test and, thus, not particularly appropriate for fiber-reinforced concrete.
- While the results of the test are related to yield stress, the results are not recorded in fundamental units.

3.1.2.7 Moving Sphere Viscometer

The moving sphere viscometer (Powers 1968; Wong et al. 2000) uses the principle of Stoke's law to measure the viscosity of concrete. Falling object and drawn object viscometers have been used widely in measuring the viscosity of other materials. A similar test device, the turning tube viscometer, is used for pastes.

To perform the test, concrete is placed in a rigid container, which can be attached to a vibrator in order to measure the concrete's behavior under vibration. A steel sphere is then either pushed or pulled through the concrete. The test can be conducted either by applying a constant force to the sphere and recording the location of the sphere in the concrete versus time or by pushing or pulling the sphere through the concrete at a fixed rate and measuring the force required to move the ball. Using Stoke's law, the viscosity of the concrete is then calculated as a function of the velocity of the sphere and the force required moving the sphere. Correction factors must be applied to account for assumptions made with regard to Stoke's law.

Wong et al. (2000) recently explored the possibility of developing a moving object viscometer for use with low slump concretes. The researchers encountered difficulty in determining a constant, steady state value of force required to pull a sphere through concrete. Although the researchers did not recommend such a moving object viscometer for use with low-slump concretes, they did suggest a conceptual field system.

Advantages:
- The physics of the test are well known, allowing viscosity to be measured.
- The test can measure the effect of vibration on viscosity.

Disadvantages:
- The sphere should be significantly larger than the maximum aggregate size. As a result, the concrete sample must be quite large in order to accommodate typical aggregate sizes.
- The test does not provide a direct result. The velocity of the sphere and the force applied to the sphere must be measured and used in an equation to calculate viscosity. Additionally, correction factors must be applied.
- While the test does provide a measure of plastic viscosity, it does not provide a direct measure of yield stress.

- Although a conceptual field device has been proposed, the test method would likely be limited mainly to the laboratory. The test is more expensive and complex than most other single-point tests.

3.1.2.8 Flow Trough Test

The flow trough test (Bartos, Sonebi, and Tamimi 2002) is used to measure the workability of highly flowable concretes. It was originally developed for measuring repair concretes.

The test apparatus consists of a 230 mm wide, 1000 mm long horizontal steel trough. Approximately 6 liters of concrete is placed in a conical hopper and allowed to fall from the hopper onto one end of the trough. The time required for concrete to flow a certain distance (typically 750 mm) down the trough is recorded. The test is conducted three times immediately after mixing and another three times thirty minutes after mixing. The set of tests is conducted at thirty minutes in order to characterize the workability of the concrete at the time of placement. The concrete is agitated every five minutes in the thirty minutes between the initial and final sets of tests.

Advantages:
- The test method is simple and inexpensive.
- The results are a function of the time required for the concrete to flow both out of the cone and down the trough.

Disadvantages:
- The test is only appropriate for highly flowable concrete mixtures.
- The test is not standardized and not widely used.

3.1.2.9 Delivery-Chute Torque Meter

The delivery-chute torque meter (US patent 4,332,158; Wong et al. 2000) is designed to measure the consistency of concrete as it exits a concrete mixing truck. The intent of the device is to measure slump accurately without having to wait for the conventional slump test to be performed.

The hand-held device, which is shown in Figure 7, is inserted in flowing concrete in the delivery chute of a concrete mixing truck. The two curved sensing blades are attached to a vertical member that measures torque. The device is inserted in the delivery chute such that the sensing blades are orthogonal to the flow of concrete. The flowing concrete applies approximately equivalent forces to each of the two sensing blades. These forces create opposing moments on the inner vertical member. Since the length of the moment arm for the right sensing blade is approximately twice that of the moment arm for the left sensing blade, a net torque is applied to the inner vertical member. The operator manually applies an opposing torque to the outer housing to keep the blades orthogonal to the flow of concrete. The magnitude of this applied torque is indicated on the flat circular plate located just above the two sensing blades. The torque measured with the device is correlated to slump, with the appropriate correlation marked on the circular plate. For concretes with different viscosities, different calibrations must be

obtained. The geometry of the device allows the device to adjust automatically to changes in flow velocity and height.
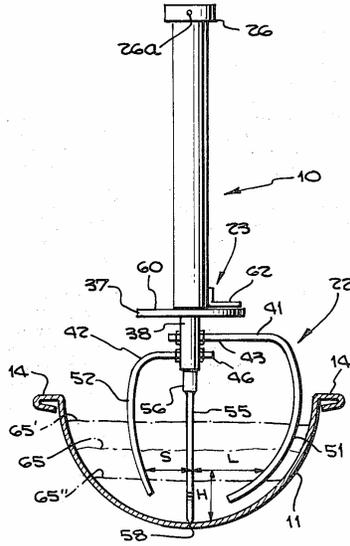
Figure 7: Delivery-Chute Torque Meter (US Patent 4,332,158)

Advantages:
- The device measures the workability of the concrete as it exits the mixer before it is placed.
- The torque (and associated slump) is read directly from the device. No computer or other sensing devices are required to determine slump.

Disadvantages:
- The torque meter is a single-point test that gives no indication of plastic viscosity. Readings are made at only one shear rate.
- The device must be calibrated for each concrete mixture.

3.1.2.10 Delivery-Chute Depth Meter

The delivery-chute depth meter (US patent 4,578,989; Wong et al. 2000) is similar to the delivery-chute torque meter in that it measures the consistency of concrete as it exits a concrete mixing truck.

The device is a triangular plate with an attached level, as shown in Figure 8. The angles at the base of the triangular plate are used along with the attached level to set the discharge chute to predefined angles. Concrete is allowed to flow down the discharge chute until it begins to fall off the end of the discharge chute. At that point, concrete flow is stopped and the device is inserted into the concrete. The height of the concrete in the chute, as measured on the triangular plate, is related to slump.

The device must be calibrated for each concrete mixture tested. For a given concrete mix, the water content is systematically altered. For each water content, the slump and the depth of flow in the delivery chute are recorded in order to develop points on the device. Given that each

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separate concrete mixture must be calibrated separately, the device is best suited for jobs where a large quantity of one concrete mixture is being placed.
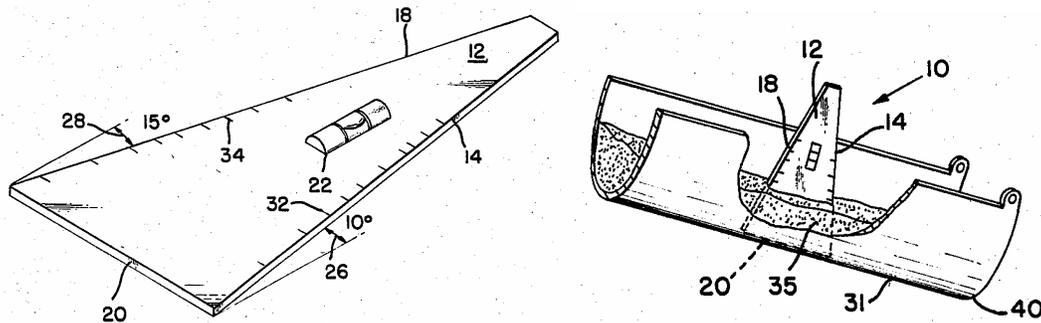
Figure 8: Delivery-Chute Depth Meter (US Patent 4,578,989)

Advantages:
- The device allows workability to be judged quickly before any concrete exits the end of the delivery chute.
- The device is simple and inexpensive.

Disadvantages:
- The device must be calibrated for each concrete mixture.
- Any variations in concrete height along the length of the delivery chute could distort readings.

3.1.2.11 Surface Settlement Test

The surface settlement test (Bartos, Sonebi, and Tamimi 2002) is used to assess the stability of concrete by measuring the settlement of fresh concrete over time. The test is most appropriate for highly fluid and self-compacting concretes; however, it can be used for moderate slump concrete mixtures.

The test apparatus consists of an 800 mm tall, 200 mm diameter pipe sealed at the bottom. Two longitudinal seams allow the pipe to be removed once the concrete sample has hardened. To perform the test, concrete is filled to a height of 700 mm in the cylinder. Highly fluid and self-compacting concretes do not need to be consolidated; however, rodding or vibration is necessary for less fluid concretes. A 4 mm thick, 150 mm diameter acrylic plate is placed on the top surface of the concrete. Four 75 mm long screws extend downward from the acrylic plate and into the concrete. A linear dial gauge or linear variable differential transformer (LVDT) is used to measure the settlement of the acrylic plate over time until the concrete hardens. The top of the pipe is covered during the test to prevent evaporation. In addition to a plot of surface settlement versus time, the maximum surface settlement versus initial concrete height is computed.

Advantages:
- The test is inexpensive and simple to perform.
- The test is appropriate for a wide range of concrete mixtures.

Disadvantages:
- The test does not give a direct result.
- The time required to perform the test is substantially longer than other test methods because the settlement distance must be recorded until the concrete hardens.

3.1.3   Vibration Test Methods

Due to the wide use of vibration in placing concrete, many test methods measure the flow of concrete under vibration. Vibration test methods typically feature free or confined flow. Vibration test methods are generally simple to perform; however, none has been widely accepted. Although vibration test methods can be used for a wide range of workability, they are most appropriate for low and moderate slump concretes that are commonly vibrated in the field. Additionally, it should be noted that some rotational rheometers are capable of measuring the rheology of concrete under vibration.

In evaluating the results of vibration test methods, it is important to recognize the role of several vibration parameters in influencing the flow properties of concrete. It has been experimentally established (Tattersall and Baker 1989; Banfill, Yongmo, and Domone 1999) that vibration alters the Bingham parameters of concrete. The flow properties of vibrated concrete are related not just to the flow properties of the unvibrated concrete but also to the nature of the applied vibration. Banfill, Yongmo, and Domone (1999) has shown that the flow of concrete under vibration is most significantly influenced by the velocity of the vibration. When the velocity of vibration is above a minimum threshold value, concrete can be considered a Newtonian fluid, at least for low shear rates. Based on this information, the results obtained from the same test method but with different types of vibration should generally not be directly compared. Since most test methods in this document have not been standardized, they do not have one single specified type of vibration. Ideally, the vibration applied by the test should closely match the vibration applied in the field.

3.1.3.1   Compaction Test (Walz Test, Compaction Index Test, Degree of Compaction Test)

Like the compaction factor test, the compaction test (Bartos 1992; Bartos, Sonebi, and Tamimi 2002) expresses workability in terms of the compactability of a concrete sample. The test was developed during the 1960s in Germany and is standardized in Europe as EN 12350-4.

The test apparatus, shown in Figure 9, is extremely simple—it consists merely of a tall, rigid metal container with side dimensions of 200 mm and a height of 400 mm. The top of the container is open. The container is filled with fresh concrete without compaction. After the top of the filled container has been struck off level, the concrete is compacted with a tamping rod or, more commonly, with vibration until the concrete ceases to subside in the box. According to the European standard, EN12350-4, the concrete must be compacted using an internal or external vibrator operating at a specified frequency. The distance from the top of the concrete to the top of the container is measured at the four corners of the container. The degree of compaction is calculated as the height of the container divided by the average height of the compacted concrete.

Typical test results range from 1.02 to 1.50. Unlike the compaction factor test, a standard amount of energy is not imparted into the system.
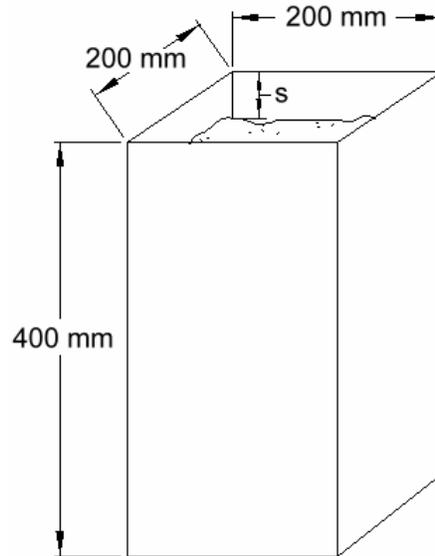
Figure 9: Compaction Test Apparatus

A similar test, the Fritsch test (Ferraris 1999), measures not just the distance that the concrete compacts, but also the time for this compaction to occur. An internal vibrator is placed inside a mold of fresh concrete. The time for the concrete to obtain full compaction and cease falling is recorded as a measure of workability. A settling curve is developed by plotting the height of concrete in the container versus time. Another similar test has been presented by Leivo (1990).

Advantages:
- The compaction test provides an indication of the compactability of concrete.
- The test device is simple and inexpensive.
- When the variable of time is added, an indirect indication of plastic viscosity is given.

Disadvantages:
- The test device can be difficult to empty, particularly when low slump concretes are tested.
- Test results with different compaction methods cannot be compared directly.
- When the time for compaction is measured, determining the end point of the test is difficult because the height of concrete in the container versus time is asymptotic. The use of a computer can facilitate the readings of height versus time and the selection of the end point of the test.

3.1.3.2 Vebe Consistometer

The Vebe consistometer (Bartos 1992; Scanlon 1994; Bartos, Sonebi, and Tamimi 2002) measures the remolding ability of concrete under vibration. The test results reflect the amount of energy required to remold a quantity of concrete under given vibration conditions. The Vebe consistometer is applicable to concrete with slumps less than 2 inches.

The apparatus, shown in Figure 10, consists of a metal cylindrical container mounted on a vibrating table, which produces a sinusoidal vibration. In the version of the test standardized in Europe as EN 12350-3, a slump cone is placed in the center of the cylinder and filled in the same manner as in the standard slump test. After the slump cone is removed, a clear plastic disk is set atop the fresh concrete. The Vebe table is started and the time for the concrete to remold from the slump cone shape to the shape of the outer cylindrical container is recorded as a measure of consistency. The sliding clear plastic disk facilitates the determination of the end of the test.
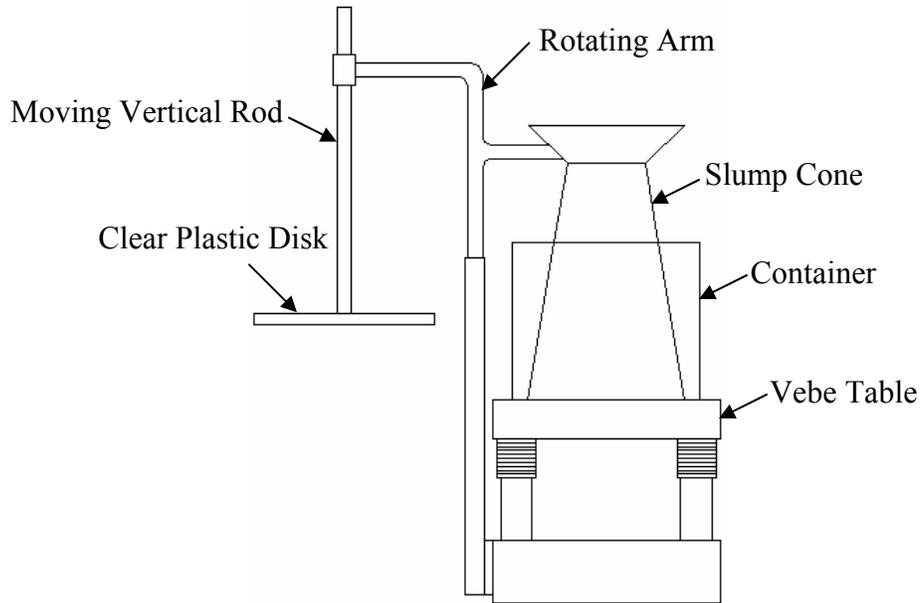
Figure 10: Vebe Consistometer

Juvas (1994) has presented a modified Vebe test to more efficiently measure low slump concretes that exhibit standard Vebe times greater than 30 seconds. In the modified Vebe test, a 20 kg surcharge is attached to the rod above the clear plastic disk. The remainder of the test apparatus and procedure is unchanged. The modified Vebe test more closely represents the production of precast concrete elements that are both vibrated and pressed.

ASTM C1170 describes two variations on the procedure described above for use with roller-compacted concrete. Instead of placing concrete in a slump cone in the cylinder, concrete is placed directly into the 9 ½-inch diameter, 7 ¾-inch tall cylinder without compaction. For Test Method A, a 50 pound surcharge is placed on the sliding plastic disk. The vibrator is started and the time for the concrete to consolidate and a mortar ring to form around the plastic disk is recorded. The surcharge is then removed and the concrete is vibrated further until the total vibration time is 2 minutes. The density of the consolidated concrete in the mold is then determined. When the Vebe time by Test Method A is less than 5 seconds, Test Method B should be used. In Test Method B, the surcharge is not used. Both the time for a mortar ring to form around the perimeter of the cylinder and the final density of the compacted concrete are

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recorded. Both methods are applicable for concretes with maximum aggregate sizes up to 2 inches. A minimum of 50 pounds of concrete is required for each test method.

Since the test apparatus is large and heavy, it is inappropriate for field use. The vibrating table must be mounted on a large and stable base of sufficient mass to absorb the table's vibrations. The main use for the test has been in the laboratory and in the precast industry, where low slump concrete mixes are commonly used (Bartos 1992). The apparatus is neither directly related to slump nor plastic viscosity.

Advantages:
- The Vebe consistometer is a dynamic test and can be used on concretes that are too dry for the slump test.
- The test device is standardized in ASTM and identified by ACI Committee 211 (2002) in its guide for proportioning low slump concrete.
- Test results are obtained directly.

Disadvantages:
- Due to the need to ensure that all vibration is kept within the test device, the size of the test device makes the Vebe consistometer generally unsuitable for field use.
- The test device only works for low slump concretes.
- No analytical treatment of the test method has been developed. Such treatment would be complex because the shear rate declines during the duration of the test as the concrete specimen changes shape.

3.1.3.3 Powers Remolding Test

The Powers remolding test (Powers 1968; Scanlon 1994; Wong et al. 2000) is similar to the Vebe consistometer. The test was develop by Powers and first presented in 1932. The test has been standardized by the US Army Corp of Engineers as CRD C6-74.

The test apparatus consists of a 12 inch diameter cylindrical mold mounted on a standard drop table, described in ASTM C124 (which was withdrawn in 1973). A separate 8 ¼ inch diameter ring is attached at the top of the cylinder, as shown in Figure 11. The concrete sample is compacted in the standard slump cone inside of the inner ring. Like the Vebe consistometer, a clear plate attached to a vertical stem rests on top of the concrete. The number of drops required to remold the concrete to the shape of the outer cylinder is a measurement of the "remolding effort."

The ring attached to the outer cylinder restricts the movement of the concrete and allows for the determination of the plastic shear capacity of the concrete mix. A mix with high shear capacity easily passes under the ring, whereas mixes with low shear capacity tend to clog and result in greater required remolding effort. It is possible that two mixes that require the same remolding effort when the ring is removed require different remolding efforts when the ring is in place.

Research has shown that the Powers remolding test is more sensitive to changes in workability than the slump test (Scanlon 1994).
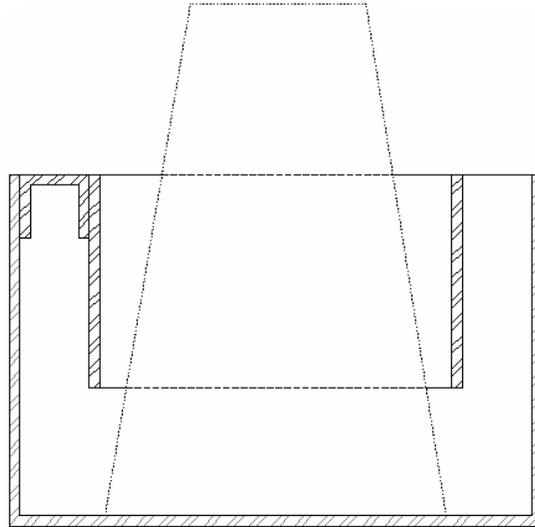
Figure 11: Powers Remolding Test Container Incorporating Inner Ring

Advantages:
- The Powers remolding test is a dynamic test and is suitable for low slump concretes.
- The results of the test are obtained directly.

Disadvantages:
- The drop table must be mounted on an object of sufficient mass to absorb vibrations created by the drop table. Accordingly, the device is likely to be too large and bulky for field use.
- The test method is only suitable for low slump concretes.
- No analytical treatment or experimental testing of the test method has been performed to relate the test results to yield stress and/or plastic viscosity.

3.1.3.4 Thaulow Tester

The Thaulow concrete tester (Powers 1968; Scanlon 1994; Wong et al. 2000) is similar to the Vebe consistometer and the Powers remolding test, but is modified to allow for the measurement of concretes with higher workability.

The apparatus consists of a 10 liter cylinder of smaller diameter than the containers used in the Vebe consistometer and the Powers remolding test. The cylinder is attached to a drop table. A handle is mounted with pins at the top of the cylinder. A mark on the cylinder at 5 liters assists in determining the end of the test. Concrete is placed in the cylinder using the standard slump cone. For concretes with moderate workability, the handle is allowed to fall from its vertical position and strike opposite sides of the container until the concrete remolds to the 5 liter mark on the container. For low slump concretes, the number of drops of the table required to remold the sample to the 5 liter mark is recorded.

The Thaulow concrete tester is applicable mainly to low slump concrete. ACI Committee 211 (2002) has recommended using the Thaulow concrete tester for concretes that are too dry to be measured with the slump cone.

Advantages:
- The Thaulow concrete tester is a dynamic test method.
- The handle attached to the cylinder allows for the measurement of concretes with higher workability than can be measured with the Vebe consistometer and the Powers remolding test.
- Test results are obtained directly.

Disadvantages:
- The drop table must be mounted on an object of sufficient mass to absorb vibrations created by the drop table. Accordingly, the device is likely to be too large and bulky for field use.
- No analytical treatment or experimental testing of the test device has been performed to relate the test results to yield stress and/or plastic viscosity.

3.1.3.5 Flow Table Test (DIN Flow Table)

The flow table test (Tattersall 1991; Bartos 1992; Wong et al. 2000; Bartos, Sonebi, and Tamimi 2002) measures the horizontal spread of a concrete cone specimen after being subjected to jolting. Multiple versions of the test have been proposed since its original introduction in Germany in the 1930s. The test was added to the British Standards in 1983 in response to the increase use of highly fluid concretes. The test is sometime referred to as the DIN flow table, in reference to its inclusion in German standard DIN 1048. The test is currently standardized in the Europe as EN 12350-5.

The apparatus consists of a 700 mm square wooden top plate lined with a thin metal sheet, as shown in Figure 12. The plate is hinged on one end to a base, while on the other end, clips allow the plate to be lifted a vertical distance of 40 mm. Etched into the metal sheet are two perpendicular lines that cross in the center of the plate and a 200 mm circle concentric with the center of the plate. The frustum of a cone used to mold the concrete is shorter than the slump cone, with a top diameter of 130 mm and with a bottom diameter and height of 200 mm.
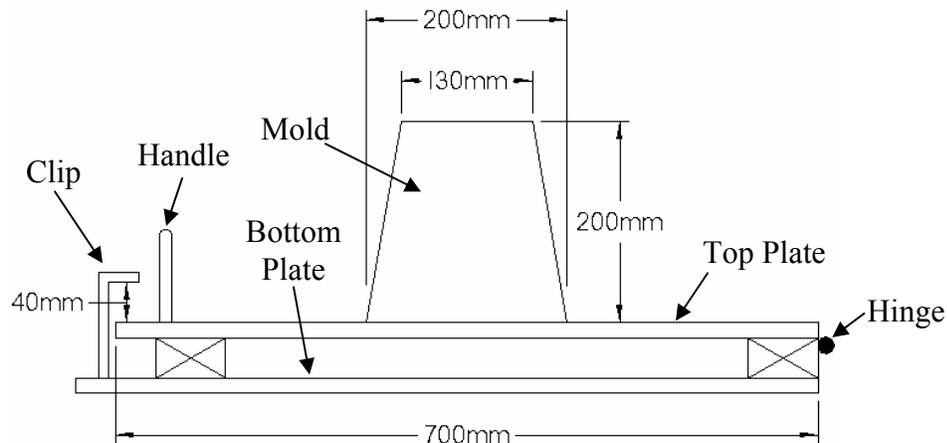
Figure 12: Flow Table Test Apparatus

To perform the test, the cone mold is placed in the center of the plate and filled in two layers, each of which is compacted with a tamping rod. The plate is lifted with the attached handle a distance of 40 mm and then dropped a total of 15 times. The horizontal spread of the concrete is measured. Resistance to segregation can be assessed qualitatively: in concrete mixes that are susceptible to segregation, the paste will tend separate from the coarse aggregate around the perimeter of the concrete mass.

The test is applicable to a wide range of concrete workability, and is especially appropriate for highly fluid mixes that exhibit a collapsed slump. The results of the test can be correlated to slump, although it has been suggested that the initial horizontal spread, prior to jolting, correlates better to slump (Juvas 1994). Despite its simplicity, the test apparatus is large and must be placed on firm, level ground. The jolting of the concrete does not accurately simulate field practices and cannot easily be treated analytically. In fact, the further the concrete spreads, the thinner the layer of concrete becomes and the less this thin layer represents the bulk properties of the concrete. Research has suggested that spread measurements for different concrete mixtures converge with an increasing number of drops of the top plate (Tattersall 1991).

Advantages:
- The test is simple and can be used in the field.
- The test quickly provides a direct result.
- The test is dynamic, making it especially appropriate for highly thixotropic concrete mixtures.

Disadvantages:
- The test procedure does not represent actual placement conditions—concrete is typically vibrated, not jolted.
- The test results tend to converge as the number of drops is increased. Near the end of the test, the properties of the thin layer of concrete do reflect the bulk properties of the concrete.
- The results are not given in terms of fundamental units. An analytical treatment of the test would be difficult.

3.1.3.6 Angles Flow Box Test

The Angles flow box test (Scanlon 1994; Wong et al. 2000) attempts to simulate typical concrete construction in order to characterize the ease with which concrete can be placed. The test measures the ability of concrete to flow under vibration and to pass obstructions.

The device consists of a rectangular box mounted on a vibrating table. Two adjacent vertical partitions are placed in the middle of the box to divide the box in half. The first partition consists of a screen of circular bars that are spaced so that the openings between the bars are the size of the maximum aggregate. The second partition is a solid, removable plate that initially holds concrete on one side of the box prior to the beginning of the test. After concrete has been loaded on one side of the box, the solid partition is removed and the vibrating table is started. The time for the concrete to pass through the screen and form a level surface throughout the box is recorded. The amount of bleeding and segregation that occurs during vibration can be observed visually.

Very little data is available on the validity of the test and on interpretation of the test results. The test method would not be appropriate for very low slump mixes. For highly flowable concrete mixtures, vibration may be unnecessary. A similar concept is used to test the workability of self-compacting concrete.

Advantages:
- The test method represents actual field conditions. It is a dynamic test that subjects concrete to vibration.
- The ability of concrete to pass obstructions and resist segregation is assessed.

Disadvantages:
- The test is bulky and would probably not be appropriate for field use.
- The test result is likely a function of both yield stress and plastic viscosity, although these values are not directly recorded.

3.1.3.7   LCL Flow Test

The LCL flow test (Bartos 1992; Ferraris 1999; Bartos, Sonebi and Tamimi 2002) is very similar to the Angles flow box test. The test is suitable for concretes with low and moderate workability and is not appropriate for concretes with very low or very high workability.

The device consists of a 150 mm by 600 mm rectangular box with a height of 150 mm. An external vibrator is attached to one end. A triangular wedge holds uncompacted concrete in the opposite end of the box. Rubber supports beneath the box isolate the box and absorb vibrations. To start the test, the wedge is removed and the vibrator is started. The time for concrete to spread to the other end of the box and fill to a line marked on the side of the box is measured. The results of the LCL flow test are related to plastic viscosity. Further, yield stress could be determined by slowly increasing the amplitude of vibration until the concrete begins to flow.

Although the test provides a direct and usable result, the device must be calibrated using a standard aggregate and a standard mix design in order to interpret the results further. The difficulty in determining the endpoint of the test reduces the precision of the test results. Two sizes of the device exist: one for normal concrete and another for mortars and concretes with maximum aggregate size less than 12.5 mm. The larger device requires 35 liters of concrete.

Advantages:
- The LCL flow test is a dynamic test, capable of measuring values related to both yield stress and plastic viscosity.
- The test partially represents actual field conditions.
- A direct result is quickly obtained.

Disadvantages:
- The test is more expensive and complicated than the slump test and requires electricity, thus reducing the likelihood it would be used in the field.
- Although the test does measure values related to yield stress and plastic viscosity, the values are not determined in fundamental units.
- The precise end point of the test can be difficult to determine.

3.1.3.8 Wigmore Consistometer

The Wigmore consistometer (Scanlon 1994) is a dynamic penetration test that was developed as an improvement of the slump test. The test measures consistency by adding energy to the concrete and measuring penetration resistance.

The apparatus consists of cylindrical container mounted on a drop table. A removable lid placed atop the cylinder includes a hole that guides a graduated rod with an attached 2 inch ball vertically downward through the concrete. To perform the test, concrete is placed into the container and compacted with eight drops of the table. The container is filled to the top and struck off level. The lid with the rod and ball is placed on top of the container. The number of drops required to lower the ball 7 ¾ inches into the concrete is recorded as a measure of consistency.

Typical results vary from 20 drops for soft and fluid concrete to 200 drops for stiff, low slump concrete. Large aggregates can interfere with the descent of the ball and lead to variability in the test results.

Advantages:
- The Wigmore consistometer is a dynamic test that provides a direct result.
- The test can be used on a wide range of concrete workability.

Disadvantages:
- In order to minimize the disproportionate effects of coarse aggregate particles on test results, the ball should be significantly larger than the maximum coarse aggregate size. Such a test device would be impractically large.
- Although the results of the test are related both to yield stress and plastic viscosity, results are not expressed in fundamental rheological units.
- The drop table must be mounted on an object of sufficient mass to absorb vibrations created by the drop table. Accordingly, the device is likely to be too large and bulky for field use.

3.1.3.9 Vibropenetrator

The Vibropenetrator was developed by Komlos (1964) as a penetration test to measure the behavior of vibrated concrete. The device consists of a standard 20 cm cube mold mounted on a vibrating table. Concrete is placed in the mold and compacted with the assistance of the vibrating table. A rod, which is guided by a sleeve mounted to the cube mold, is placed on top of the concrete. The vibrating table is started and the time for the rod to penetrate a certain depth into the concrete is measured as an indication of workability. A ring on the rod touches the top of the sleeve to indicate the end point of the test. Komlos performed the test on moderate to highly workability concretes with water/cement ratios ranging from 0.38 to 0.90.

The Vibropenetrator test has the advantage of being a dynamic test that adds energy to the concrete. The results of the test are a function of not just the concrete properties, but also the nature of the applied vibration. Large coarse aggregates could interfere with the descent of the rod and distort test results.

Advantages:
- The Vibropenetrator test is a dynamic test that measures the behavior of vibrated concrete.
- The test is simple to perform and provides a direct result.

Disadvantages:
- Large coarse aggregates could distort test results by interfering with the descent of the penetrating rod.
- Although the test has been performed on a wide range of concrete workability, highly flowable concrete with a water cement ratio near 0.90 would likely be difficult to test with precision.
- The test requires a vibrator and electricity and is not as simple as other single-point field tests.

3.1.3.10 Inverted Slump Cone Test

The inverted slump cone test (Tattersall and Banfill 1983; McWhannell 1994; Johnston 1994; ASTM C995-01; Bartos, Sonebi, and Tamimi 2002) was developed as a simple and inexpensive field test to measure the workability of fiber-reinforced concrete. Although fiber-reinforced concrete can show increased workability, the individual fibers act to increase concrete thixotropy. McWhannell (1994) has shown that mixes incorporating polypropylene fibers show a slight decrease in slump but an increase in workability as measured with the compacting factor test. Indeed, SI Concrete Systems, a large manufacturer of steel and synthetic fibers for concrete, advises against using the slump test for measuring the workability of fiber-reinforced concrete.

The test apparatus is comprised of readily available jobsite equipment—an internal vibrator, slump cone, and bucket. The test is standardized in ASTM C995: "Standard Test Method for Time of Flow of Fiber-Reinforced Concrete through Inverted Slump Cone." A specially constructed wood frame, shown in Figure 13, holds the slump cone in an inverted position above the standard bucket described in ASTM C29/C29M for determination of unit weight. A 4 inch gap is left between the bottom of the inverted slump cone and the bottom of the bucket. The dampened slump cone is then filled with concrete in three layers. Although the concrete should not be compacted, each layer of concrete should be leveled off to minimize entrapped air. To keep the concrete from falling through the bottom of the slump cone, the ASTM standard recommends placing a sufficiently large volume of concrete in the bottom of the cone to bridge the opening. With the slump cone full and leveled off at the top, a one-inch diameter internal vibrator is inserted into the top of the concrete and allowed to descend at a rate such that the vibrator comes into contact with the bottom of the bucket in 3 +/- 1s. The vibrator is then held in a vertical position and the total elapsed time from the insertion of the vibrator until all the concrete has passed out of the slump cone is recorded.
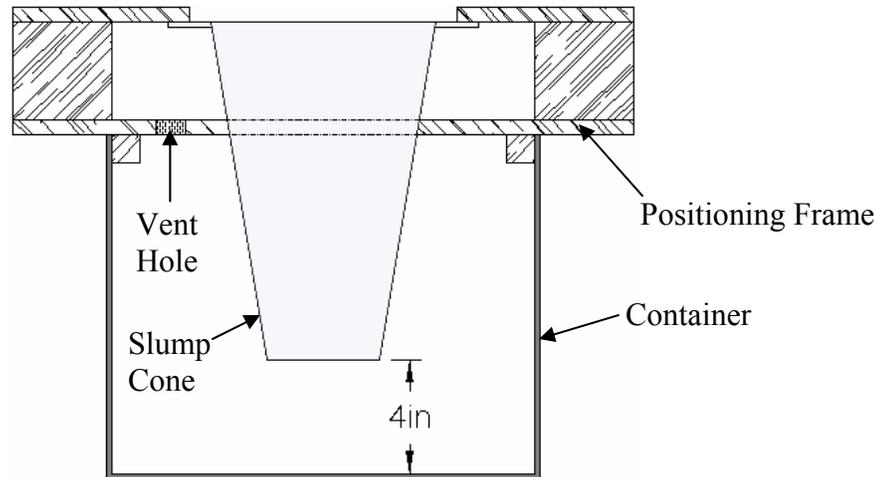
Figure 13: Inverted Slump Cone Test Apparatus

ACI Committee 544 (1989) on fiber-reinforced concrete recommends the use of the inverted slump cone test. The use of vibration has been deemed appropriate since the fiber-reinforced concretes that are tested with the inverted slump cone test are commonly vibrated during placement. Research has shown that the inverted slump cone test can successfully detect changes in coarse aggregate fraction, fiber content, fiber length, and fiber aspect ratio (Johnston 1994).

Although the test is improvements on static tests that do not take into account the higher thixotropy of fiber-reinforced concrete, the inverted slump cone test has several important restrictions on its usefulness. The test applies only to concretes with flow times greater than 8 seconds and slumps less than 2 inches. More fluid concretes can flow through the bottom of the cone without vibration and cannot be measured with sufficient precision. The size of the apparatus also restricts the use of some concretes. The small gap of 1 ½ inches around the vibrator at the bottom of the cone limits the maximum aggregate size and the use of long, stiff fibers with high aspect ratios. Tattersall and Banfill (1983) state that the gap between the cone and vibrator should be 10 times the maximum aggregate size. Additionally, long fibrillated and monofilament fibers can wrap around the vibrator and distort results. In order to allow the use of readily available job equipment to conduct the test, the ASTM standard only specifies that the internal vibrator be 1 +/- 1/8 inch in diameter. Variations in the diameter, frequency, and amplitude of the vibrator prevent the direct comparison of test results and the development of specifications for fiber-reinforced concrete in terms of inverted slump cone time. The precision of the test is influenced by operator error in properly inserting the vibrator and determining the correct start and stop times for the test. Since the concrete is not consolidated prior to the start of the test, the cone can contain large volumes of entrapped air.

Advantages:
- The inverted slump cone test is a dynamic test that takes into account the high thixotropy of fiber-reinforced concrete.
- The test is simple and provides a direct result.
- The test apparatus consists of readily available equipment.

Disadvantages:
- The test is only appropriate for concrete mixes with a slump of less than 2 inches.
- The test is difficult to perform. Filling the inverted slump cone with concrete so that no concrete falls through the hole is tricky. Further, the vibrator must be inserted directly down the center of the inverted slump cone in a certain period of time.
- The gap at the bottom of the inverted slump cone is too small based on typical aggregate sizes and some fiber lengths.
- Some long fibers may wrap around the vibrator.
- Important test parameters are not standardized; therefore, tests conducted with different vibrators cannot be compared. Likewise, it is difficult to write specifications in terms of inverted slump cone time.
- Operator error is introduced in determining the exact stopping point of the test.

3.1.3.11 Vertical Pipe Apparatus

The vertical pipe apparatus (Tattersall and Baker 1989; Banfill, Yongmo, and Domone 1999) was developed as a laboratory device to measure the effects of vibration on fresh concrete.

The device, which is depicted in Figure 14, consists of a 100 mm diameter, 700 mm long vertical pipe mounted above a metal cylindrical container that is attached to a vibrator. A sliding sleeve holds concrete in the pipe initially. A block attached to the container ensures that when the sleeve is lifted, concrete flows horizontally out of the pipe and is not blocked by concrete already in the cylindrical container. The block is 70 mm tall and the gap between the block and the pipe is 60 mm. To begin the test, the vibrator is started and the sleeve is lifted to allow concrete to flow out of the pipe. An ultrasonic displacement transducer above the pipe of concrete measures the height of the concrete in the pipe versus time. In older versions of the test, a tape measure was used to measure this distance.
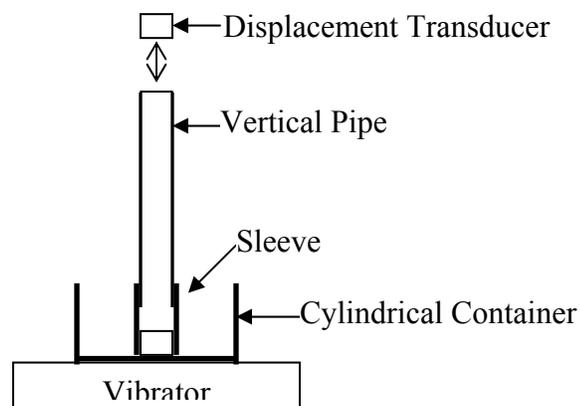
Figure 14: Schematic of the Vertical Pipe Apparatus

The test is based on the principle that concrete behaves as a Newtonian fluid when subjected to vibration. The rate of flow of a Newtonian fluid in a vertical pipe is a function of the head, *H*, as shown in Equation [8], where *b* is the constant of proportionality expressing fluidity.

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$$\frac{dH}{dt} = -bH \qquad\qquad [8]$$

The vibrator must be a simple wave-form vibrator with independent control of frequency and velocity. An inexpensive eccentric type or a common commercial vibrator would not allow the study of the effects of different vibration parameters on concrete.

Advantages:
- The vertical pipe apparatus is a dynamic test that provides valuable information on the flow of concrete under vibration.
- By changing the vibration parameters, the test can be used to determine values related to yield stress and plastic viscosity.

Disadvantages:
- The test is expensive and may not be appropriate for field use. The test does not provide a direct result.
- The 60 mm size of the opening below the pipe is too small for most aggregate sizes.
- For highly flowable concretes, the concrete will quickly flow out of the pipe without the assistance of vibration.

3.1.3.12 Vibrating Slope Apparatus (VSA)

Originally developed in the 1960s, the vibrating slope apparatus (Wong et al. 2000) was recently modified by the US Army Engineering Research and Development Center (ERDC) for the US Federal Highway Administration (FHWA). The device measures the workability of low slump concretes subjected to vibration at two different shear rates in order to determine a "workability index" that is related to plastic viscosity and a "yield offset" that is related to yield stress. Researchers at the ERDC selected the vibrating slope apparatus over twenty other workability test devices as a superior choice to measure the workability of low slump concretes in the field.

The vibrating slope apparatus as modified by the US Army Engineering Research and Development Center is shown in Figure 15. Concrete to be tested is placed in the chute, which can be set at a predefined angle. Three load cells continuously measure the mass of concrete in the chute during the test. Small transverse metal strips reduce slip between the concrete and the bottom of the chute. A vibrator is mounted to the bottom of the chute. Eight vibration dampers ensure that the vibration is applied to the concrete and that the entire apparatus does not excessively vibrate and interfere with load cell measurements. Readings from the load cells are transmitted to a laptop computer, where the workability index and yield offset are calculated. The entire apparatus is designed to be rugged and easily portable.
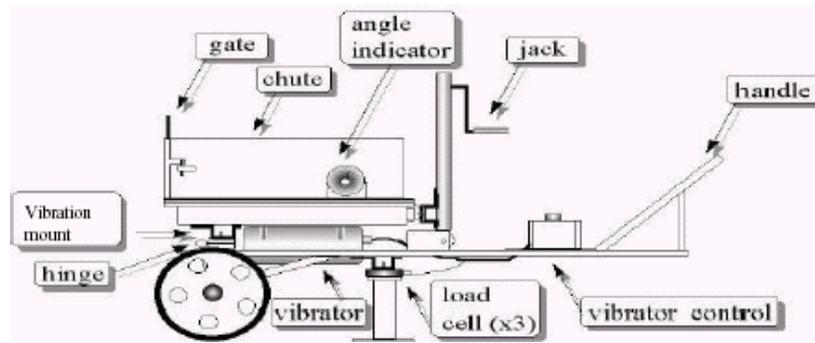
Figure 15: Vibrating Slope Apparatus (Wong et al. 2000)

To operate the device, concrete is placed in the chute, which is set at a predefined angle (typically 10-15 degrees). The gate is opened and the vibrator is started, allowing concrete to fall from the chute into a bucket. The data from the load cells is used to calculate the discharge rate. Since the discharge rate generally decreases as concrete flows out of the chute, the maximum discharge rate is recorded. The test procedure is repeated a second time for a different incline angle. The results of the test are plotted as a graph of maximum discharge rate versus discharge angle. The straight line connecting the two data points is defined by Equation [9]:

$$R = WA + C \qquad\qquad [9]$$

where R = maximum discharge rate, W = workability index, A = discharge angle, and C = calculated yield offset.

The intent of the research conducted by the ERDC for the FHWA was simply to determine if the vibrating slope apparatus would operate properly, not whether the device could accurately measure concrete rheology. The results of the preliminary ERDC laboratory testing were compared only to the slump and air content of each concrete mixture. Further, no analytical treatment of the test has been presented. Wong et al. (2000) claims that the y-intercept of the discharge rate versus discharge angle plot is the yield stress and that the slope of this plot is the dynamic viscosity; however, no effort is made to relate these parameters to fundamental units or confirm the validity of the test results. Since the yield stress of vibrated concrete is lower than the yield stress of unvibrated concrete, the yield stress recorded by the vibrating slope apparatus is not equivalent to the yield stress of the unvibrated concrete and is only applicable for the specific vibration applied by the vibrating slope apparatus. Before the vibrating slope apparatus can be used on a wider basis, the validity of the test results must be verified.

The ERDC researchers encountered multiple problems in developing the vibrating slope apparatus prototype. Many of the problems were trivial and easily corrected. Other problems will require further work to resolve. The test device is large, bulky, and weighs 350 pounds. The ERDC researchers give no cost information in their report and do not compare the cost effectiveness of the vibrating slope apparatus to other test methods.

Advantages:
- Unlike many rheometers, the device measures the workability of low slump concretes.
- The results of the device are given in terms of parameters related to yield stress and plastic viscosity.
- The device is designed to be rugged for field use.

Disadvantages:
- The results of the device have not been verified analytically or experimentally.
- The device is large, bulky, and heavy.
- Although the researchers have proposed using an embedded electronic device to record test data, the vibrating slope apparatus at this point still requires a notebook computer.
- The results of the test are only applicable for conditions with the same vibration as the vibration applied by the device.
- The shear rate is non-uniform throughout the test. The shear rate decreases as the mass of concrete in the chute decreases.

3.1.3.13 Settlement Column Segregation Test

The settlement column segregation test (Bartos, Sonebi, and Tamimi 2002) measures the degree of segregation that occurs in a concrete subjected to a standard settlement period and a standard amount of jolting. The test method is primarily intended for highly fluid concrete mixtures.

The test apparatus consists of a tall, rectangular box mounted on top of a standard mortar drop table. The column, depicted in Figure 16, is 500 mm tall and has cross sectional dimensions of 100 mm by 150 mm. Three doors on opposing sides of the box allow sections of concrete to be removed at the conclusion of the test. To begin the test, concrete is placed in the column and allowed to stand for one minute. The concrete is subsequently jolted 20 times in one minute using the drop table and then allowed to stand for an additional five minutes. The top door is then opened and the concrete behind the door is removed and saved. The concrete behind the middle door is discarded while the concrete behind the bottom door is saved. The samples from the top and the bottom of the column are individually washed through a 5 mm sieve to leave only the coarse aggregate. The segregation ratio is then calculated as ratio of the mass of coarse aggregate in the top sample to the mass of coarse aggregate in the bottom sample. The lower this ratio is, the greater the susceptibility to segregation will be.
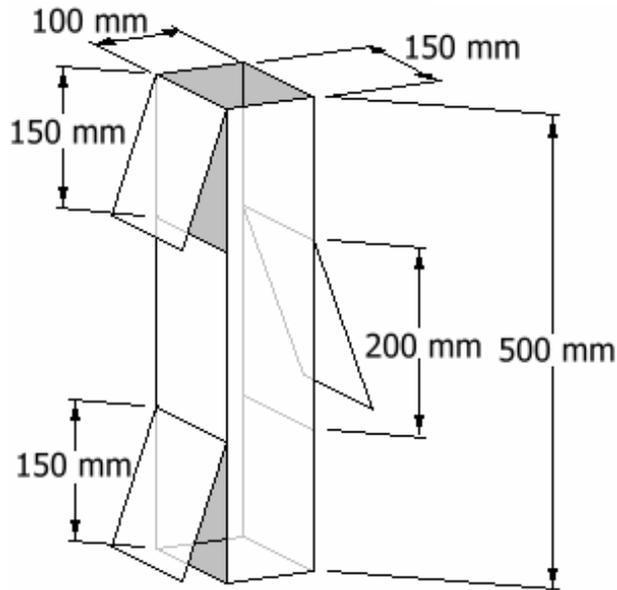
Figure 16: Settlement Column Segregation Test Apparatus

Advantages:
- The test attempts to simulate actual placement conditions.
- The test method is simple and does not require expensive equipment.

Disadvantages:
- The test is time consuming and is not practical for use in the field.
- The repeatability of test results decreases as segregation increases.

3.1.3.14 Vibratory Flow Meter

The vibratory flow meter (Szecsy 1997) was developed to measure the flow of concrete under simulated field conditions. The test method is similar to the LCL flow test, Angles flow box, and the vibrating slope apparatus.

The test apparatus, shown in Figure 17, consists of a 48 inch long, 6 inch wide, and 6 inch tall box. A vertical gate approximately one-fourth of the length from one end of the box separates the box into two sections. To conduct the test, concrete is placed in the shorter portion of the box. The gate is opened to a height of three inches and a vibrator is inserted into the concrete in the shorter portion of the box. After thirty seconds, the vibrator is removed and the distance the concrete has traveled down the box is recorded.
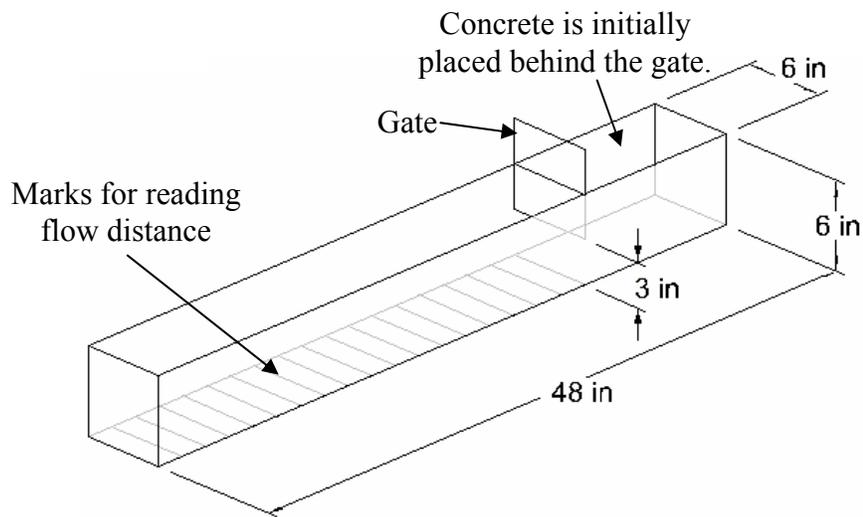
Figure 17: Vibratory Flow Meter

In testing conducted to compare the results of the vibratory flow meter to rheological parameters, Szecsy (1997) showed that vibratory flow and plastic viscosity exhibited a general relationship; however, the scatter of the data was large. Further, the vibratory flow meter was not always able to detect changes in mixture proportions. For instance, the vibrator flow meter was able to detect changes in sand content for concrete mixtures containing river gravel, but not for mixtures with a crushed limestone aggregate. The vibratory flow meter was able to detect changes in water/cement ratio and high-range water reducing admixture dosage.

Advantages:
- The test method is simple and provides a direct result.
- The test apparatus consist of readily available equipment and materials.

Disadvantages:
- Preliminary test results indicate that the device is not effective in distinguishing between changes in mixture proportions.
- The test results are dependent on the type of vibrator used. If an internal poker vibrator is used, the effect of vibration will change as concrete flows further away from the location of the vibrator.
- The test results are not given in terms of yield stress or plastic viscosity.

3.1.4   Rotational Rheometers

Many attempts have been made to adapt traditional rotational rheometers to measure concrete. Rotational rheometers for concrete apply shear stress to concrete at different shear rates in order to measure the fundamental rheological parameters of yield stress and plastic viscosity. Rotational rheometers are most typically used exclusively in the laboratory. Although some rotational rheometers have been designed to be sufficiently small and rugged for use on jobsites, the limited availability and high cost of these devices make them impractical for regular field use. Although different rotational rheometers measure different ranges of workability, various

devices are available to measure the full range of workability from low workability concrete to self-compacting concrete.

Rotational rheometers used for concrete feature parallel plate geometry, coaxial (or concentric) cylinders geometry, or impeller geometry. A parallel plate rheometer and a coaxial cylinders rheometer are depicted schematically in Figure 18. In a parallel plate rheometer, the fluid is sheared between two plates. The torque is applied and measured through one of the plates. In a coaxial cylinders rheometer, the fluid between an inner and outer cylinder is sheared. In a common arrangement of the coaxial cylinders rheometer, torque is applied to the outer cylinder while the inner cylinder measures torque. In impeller rheometers, a vane or impeller inserted into the concrete rotates at various speeds in an axial or planetary motion.

Three test methods described in this section—the soil direct shear test, the mixer devices, and the fresh concrete tester—incorporate some concepts of traditional rotational rheometers but do not measure concrete at different shear rates. These devices only determine consistency and provide no indication of plastic viscosity.
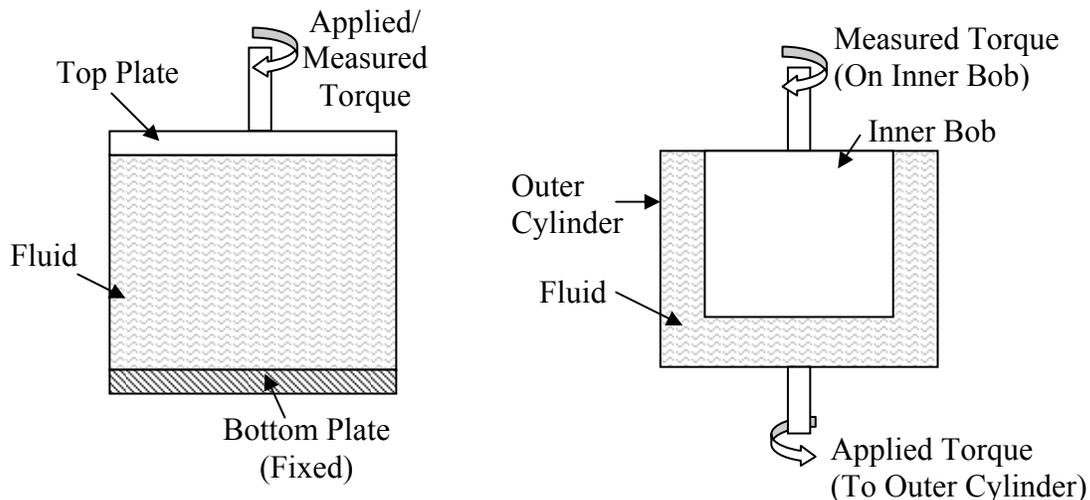
Figure 18: Schematic Drawings of a Parallel Plate Rheometer (Left) and a Coaxial Cylinders Rheometer (Right)

While traditionally rheometers have been successfully used for fine particle suspensions, concrete presents unique challenges. Unlike traditional rheometers, concrete rheometers must deal with the large size of coarse aggregates, concrete segregation, and time dependence of flow properties. For instance, in order to achieve a linear flow gradient with coaxial cylinders rheometers, the difference between the inner and outer cylinder radii should be at least five times the maximum aggregate size. Further, the ratio of the outer cylinder radius to the inner cylinder radius should be 1.0 to 1.1 (Ferraris 1999). Rheometers constructed based on these particular requirements are generally too large to be practical. Indeed, many of the problems with rotational rheometers have yet to be overcome.

3.1.4.1 Powers and Wiler Plastometer

The recording plastometer (Powers 1968; Wong et al. 2000) developed by Powers and Wiler appears to be the first attempt to apply the concept of a coaxial cylinders rheometer to concrete. Although development of the device was stopped around the time of World War II, the concepts of this first generation device have served as a basis for development of more advanced devices. The recording plastometer was designed to be of sufficient size to measure concrete, although it was also used to measure paste and mortar.

The original version of the recording plastometer was based on the classical concept of a coaxial cylinders rheometer. The outer cylinder of the recording plastometer was 12 inches in diameter and 8 inches in depth. The inner cylinder was 8 inches in diameter and 3 inches in depth and was placed 4 inches above the bottom of the outer cylinder. The outer cylinder rotated while a spring-couple system attached to the inner cylinder measured the torque applied to the inner cylinder over time. Strain was defined as the relative displacement of the outer cylinder to the inner drum. The device could be operated at different speeds or an in oscillatory motion. It was not practical, however, to use the device to measure the torque on the inner cylinder at different shear rates, as most modern rheometers now do. In a later version of the device, the outer cylinder was changed to a ring shape and the solid inner drum was replaced with a ring that split the concrete in the outer ring into two parts. The modified device is shown in Figure 19.
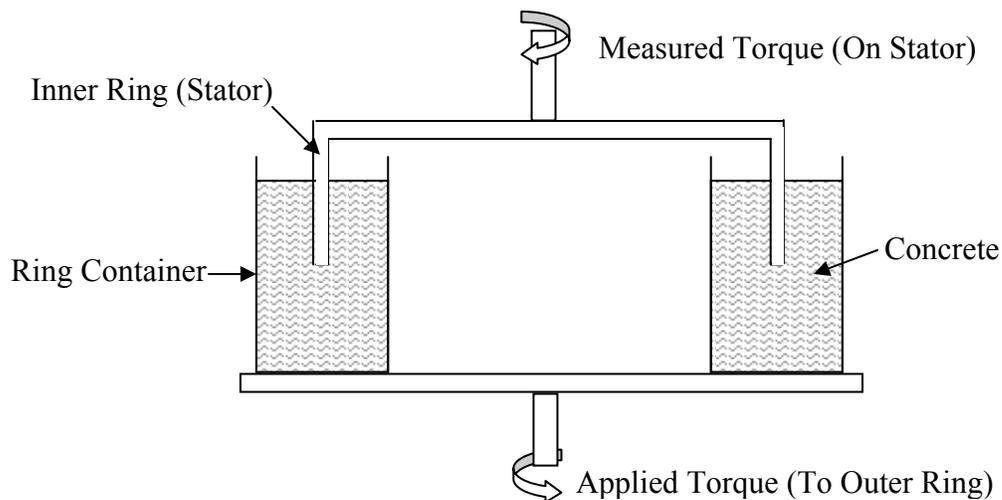
Figure 19: Revised Recording Plastometer (Not To Scale)

Despite the presence of ribbed rubber on the walls of the plastometer, slip occurred between the concrete and the plastometer walls after sufficient stress developed. The stress-strain plot up to this occurrence of this slip was linear, with the slope of the line defined as the modulus of stiffness.

Advantages:
- The recording plastometer represented one of the first attempts to use the concept of a coaxial cylinders rheometer to measure the rheology of concrete. Although it is no

longer used, the plastometer has served as a basis for the development of more sophisticated devices.

Disadvantages:
- The test measured stress and strain, not shear stress and shear rate.
- Slip occurred at the walls of the device.

3.1.4.2 Tattersall Two-Point Workability Device

The Tattersall two-point device (Tattersall and Bloomer 1979; Cabrera and Hopkins 1984; Tattersall 1990; Tattersall 1991; Ferraris and Brower 2001; Bartos, Sonebi, and Tamimi 2002) was one of the earliest attempts to measure the rheology of concrete based on the Bingham model and one of the first devices to use impeller geometry. The device has been refined over the years by Tattersall and other researchers (Wallevik and Gjorv 1990) and continues to be widely used in research.

The two-point device was originally developed by G. H. Tattersall at Sheffield University in the 1970s. Tattersall determined that coaxial cylinders rheometers would be inappropriate for measuring concrete because of the formation of a failure plane in the concrete between the cylinders. Instead, Tattersall decided to measure the torque required to turn an impeller in concrete. The development of the device began by using an ordinary food mixer fitted with a stirring hook and connected to a dynamometer wattmeter, which measured torque. This initial device was referred to as the MK I. In contrast to a coaxial cylinders rheometer, the hook of the MK I constantly came in contact with new concrete (Tattersall and Banfill 1983).

To extend the range of the initial food mixer device, a more sophisticated, specialized device was developed. This device, initially known as the MK II, is the device now commonly referred to as the Tattersall two-point device. The device consists of a stationary bowl mounted in a large frame. A hydraulic drive unit motor turns an impeller that is immersed in the concrete sample. Two different impellers are available for use based on the workability of the concrete. The MH system, which is used for slumps greater than 75-100 mm, consists of four angled blades in a helical pattern on a central shaft. The blades provide mixing action by essentially lifting the concrete. Alternatively, the LM system is intended for lower workability mixes with slumps less than 50 mm. It consists of an offset H-shaped blade that moves in a planetary motion in the concrete. When the H-shaped impeller is installed for use in a planetary motion, the device is sometimes referred to as the MK III. In addition to low slump concretes, the LM system better measures self-compacting concrete and certain high performance concretes with high plastic viscosity because this higher plastic viscosity reduces the efficiency of the mixing of the MH system. The MH and LM impeller systems are depicted in Figure 20.

In early versions of the device, the speed of the impeller was manually controlled and the torque was measured by monitoring the oil pressure in the hydraulic drive unit motor, as read from a pressure gauge. Later versions of a device use a tachometer and pressure transducer to allow continuous recording of data. The device has also been modified by adding a vibrator to characterize the effects of vibration on concrete rheology (Tattersall and Baker 1988).
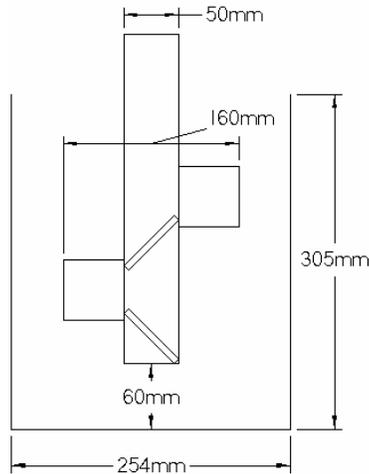
Helical Impeller (MH System)   *Offset H-Impeller (LM System)*
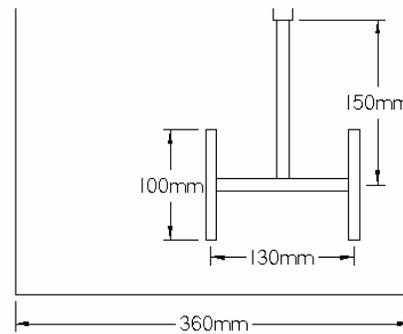
Figure 20: Impellers for Tattersall Two Point Test

The output of the device, shown in Equation [10], is given in terms of "g" and "h" which are related to yield stress and plastic viscosity, respectively. The device must be calibrated in order to determine yield stress and plastic viscosity in fundamental units. The calibration is performed using a Newtonian fluid of known viscosity and a power law fluid with a known flow curve.

$$T = g + hN \qquad\qquad [10]$$

where T = torque and N = rotation speed.

Although it was intended for use in the lab and on site (Tattersall 1991), the device has been used predominately in laboratory research.

Advantages:
- The device measures both plastic viscosity and yield stress.
- The device has been used widely in research, particularly when compared to other rheometers.
- The choice of two impellers allows the measurement of a wide range of concrete mixtures, from 2 inch slump concrete up to self-compacting concrete.
- The device can be used to measure the effects of vibration on concrete rheology.

Disadvantages:
- The test device, in its current form, is larger and bulkier than some other rheometers, particularly the BTRHEOM rheometer. The device's size limits its use in the field.
- The device must be calibrated.
- Over long periods of time, the device can cause segregation in concrete mixtures, even when segregation would not be a problem in the field.

3.1.4.3 BML Viscometer

The BML viscometer (Gjorv 1998; Ferraris and Brower 2001; Bartos, Sonebi, and Tamimi 2002) is a coaxial cylinders rheometer that is based on both the Power and Wiler plastometer and the Tattersall two-point device. The BML viscometer was developed in Norway in 1987.

Like conventional coaxial cylinders viscometers, the outer cylinder of the BML viscometer rotates while the stationary inner cylinder measures torque. Both cylinders have vertical ribs to reduce slip. The inner and outer cylinder sizes can be changed based on the size of the aggregate in the concrete being tested. At a constant angular velocity, the shear rate in the concrete is non-uniform at the bottom of the outer cylinder. Therefore, in order to more accurately measure torque, the inner cylinder is split into three parts so that only the middle section of the inner cylinder measures torque. The concrete near the middle section of the inner cylinder is subject to two-dimensional shearing, whereas the concrete in the bottom of the outer cylinder is subject to complex three-dimensional shearing. The device is operated at various fixed speeds. The cylinders are mounted on a much larger unit that houses the mechanical equipment. A computer software package converts the output data to values for flow resistance, G, and relative viscosity, H, which can then be related to yield stress and plastic viscosity, respectively.

The BML viscometer is intended for flowable concretes with slumps greater than 120 mm and can be used for self-compacting concretes. The device has also been used successfully for low slump concretes with slumps of 50-60 mm. For lower slump concretes the inner cylinder can be replaced with a blade impeller system, similar to the one used in the Tattersall two-point device. The device must be calibrated with external weights or calibration oils.

The BML viscometer has been commercially available since 1992 as the ConTec viscometer. From 1992 to February 2001, approximately thirty devices were sold (Ferraris and Brower 2001).

Advantages:
- The device measures yield stress and plastic viscosity.
- The operation of the device is automated.
- The device is appropriate for a wide range of concrete workability, although some accuracy is lost in measurements of highly flowable concrete mixtures and low workability concrete mixtures.

Disadvantages:
- Unlike the BTRHEOM, the device is too large to be used outside of a lab.
- The device is complex and expensive.
- Concrete in the shearing zone between the inner and outer cylinders has a tendency to dilate, resulting in artificially low measurements of torque.
- The device must be calibrated.

3.1.4.4 IBB Rheometer

The IBB rheometer (Beaupre and Mindness 1994; Ferraris and Brower 2001; Bartos, Sonebi, and Tamimi 2002) is a modification of the Tattersall two-point device. Although the IBB rheometer

was originally developed to measure the rheology of wet-mix shotcrete, it has been successfully used on a wide range of concretes, from concretes with a slump of 20 mm to self-compacting concretes.

The device consists of a rotating impeller inserted into a fixed cylindrical container. When testing concrete, a fixed container with dimensions 360 mm by 250 mm is used. A smaller container with dimensions 230 mm by 180 mm can be used for mortars. A computer controlled DC motor turns an H-shaped impeller capable of rotating either in a planetary motion or in an axial rotation. For concrete, a 50 mm gap is left between the impeller and the sides and bottom of the container. When the mortar setup is used, a 25 mm gap exists between the impeller and the container. Based on these dimensions, the maximum aggregate size is 25 mm for concrete samples and 12 mm for mortar samples.

A load cell measures the reaction torque from the impeller while a tachometer measures the impeller's rotation speed. Like the Tattersall two-point device, the linear relationship between torque and speed is defined by the slope h and the zero speed intercept g, which are related to plastic viscosity and yield stress, respectively. The values of g and h are calculated automatically by the computer and displayed at the end of the test. However, g is reported in terms of N-m (not the yield stress unit of Pa) and h is given in terms of N-m-s (not the plastic viscosity unit of Pa-s).

A portable version of the IBB has been developed. The device is based on the same design as the original IBB, just on a smaller scale. The portable IBB is constructed on an aluminum frame and includes wheels for easy transport.

Advantages:
- The device measures yield stress and plastic viscosity.
- The operation of the device is automated.
- The device is applicable to a wide range of concrete workability.
- The device is self-calibrating.

Disadvantages:
- The results for yield stress and plastic viscosity are not given in terms of Pa and Pa-s, respectively.
- The device, in its current form, is too large for field use. The volume of concrete required for the test is larger than for most other rheometers.
- Like the Tattersall two-point device, segregation can occur over the duration of the test, even when the particular concrete mix would not be susceptible to segregation in actual placement conditions.

3.1.4.5 BTRHEOM Rheometer

Developed in France, the BTRHEOM rheometer (de Lerrard et al. 1997; de Lerrard 1999; Wong et al. 2000; Ferraris and Brower 2001; Bartos, Sonebi, and Tamimi 2002) is a parallel plate rheometer that measures the yield stress and plastic viscosity of concrete.

The device consists of a 240 mm diameter, 100 mm tall cylindrical container with blades mounted at the top and bottom of the container. The bottom blade is fixed while the top blade rotates and measures torque. The motor is housed below the container and is connected to the top blade through a 40 mm diameter inner shaft in the concrete container. The device includes a vibrator to consolidate the concrete and to measure the effect of vibration on the rheological parameters. The test is conducted by turning the top blade at different speeds and recording the resulting torque. The torque is recorded after a 20 second period in order to allow the shear rate to stabilize.

Computer software developed for the BTRHEOM rheometer automatically calculates the Bingham parameters of yield stress and plastic viscosity. Further, the data generated in the software can be used to calculate the flow curve in terms of the Herschel-Bulkley parameters. The device records torque, Γ, and rotation speed, N, which are related according to Equation[11], where A and b are empirical constants.

$$\Gamma = \Gamma_0 + AN^b \qquad [11]$$

Equation [11] is similar to the flow equation for a Herschel-Bulkley fluid, as expressed in Equation [12] where τ = shear stress, τ_0 = yield stress, $\dot{\gamma}$ = shear velocity gradient, and a and b are empirical constants:

$$\tau = \tau_0 + a\dot{\gamma}^b \qquad [12]$$

The relationship between shear stress and the shear velocity gradient can be further simplified in terms of the Bingham parameters of yield stress and plastic viscosity, μ:

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad [13]$$

The BTRHEOM rheometer is capable of measuring dilatancy during a test. In addition to calculating the yield stress, τ_0, as shown above, the yield stress at rest can be determined using a stress controlled test. The determination of yield stress at rest is appropriate for highly thixotropic concrete mixes.

Since the initial development of the BTRHEOM rheometer, the accuracy of the device has been validated experimentally and analytically (Hu et al. 1996).

A simplified version of the BTRHEOM rheometer has been developed to eliminate several drawbacks of the original device (Szecsy 1997). In the simplified version, the motor is located above the bowl. As a result, fewer parts are necessary. Instead of using two felt seals that must be replaced frequently, the simplified version only requires a single rubber o-ring.

Advantages:
- The device measures yield stress, plastic viscosity, yield stress at rest, and dilatancy.
- The parallel plate geometry of the BTRHEOM rheometer eliminates some of the drawbacks of coaxial cylinders geometry.
- The results of the test have been verified with finite element models.
- The operation of the device is computer controlled, requiring little user intervention.
- A built-in vibrator allows the measurement of rheological properties under vibration.

Disadvantages:
- The device is complex and expensive.
- The seals must be replaced frequently. The device must be recalibrated to account for the friction caused by new seals.
- Although the device is designed to be compact and sufficiently rugged for field use, the device is too expensive for everyday field use.
- The device does not measure low workability concretes (generally with slumps less than 4 inches).

3.1.4.6 Bertta Apparatus

The Bertta apparatus (Leivo 1990; Ferraris 1999) is a coaxial cylinders rheometer that measures the fundamental rheological parameters of concrete and the compactability of concrete under shear compaction.

The Bertta apparatus features traditional coaxial cylinders geometry with outer and inner cylinders that are 480 mm and 330 mm in diameter, respectively, and 400 mm in height. Vanes attached to the outer and inner cylinders act to prevent slip. Unlike other coaxial cylinders rheometers used for concrete, the outer cylinder operates in an oscillatory mode, with a set frequency and amplitude. The stationary inner cylinder measures torque. Yield stress and plastic viscosity are calculated as a function of frequency. Generally, the shear stress is linearly related to frequency. During the test, a vertical pressure is applied to the concrete sample. The change in height of the concrete sample during the test is recorded as a measure of the compactability of concrete when subjected to shear compaction.

The geometry of the device presents problems with accurately measuring rheological parameters. Specifically, the gap between the cylinders limits the maximum aggregate size to 13 mm based on the maximum aggregate size being 1/5 of the gap size. Further, the ratio of the outer cylinder radius to the inner cylinder radius is too large for a linear flow gradient.

The device was developed at the Technical Research Centre of Finland and is not commercially available.

Advantages:
- The Bertta apparatus measures yield stress and plastic viscosity as a function of frequency while also giving an indication of compactability.
- The operation of the device is automated.
- The device can be used to measure a wide range of concrete workability, including zero-slump concretes and highly workable concretes.

Disadvantages:
- The device is likely too large for field use and requires a computer for operation.
- The geometry of the device limits the range of concretes that can be tested and reduces the accuracy of the device.

3.1.4.7 FHPCM

The Flow of High Performance Concrete Meter (FHPCM) is based on the design of the Tattersall two-point device (MKII) and was developed specifically for measuring highly flowable concrete mixtures (Yen et al. 1999; Tang et al. 2001).

The FHPCM features a coaxial cylinders geometry. The outer cylinder is 226.1 mm in diameter and 170.75 mm in height. The inner spindle is 149.9 mm in diameter, 150.75 mm in height and is set 20 mm above the bottom of the outer cylinder. The inner spindle rotates while the outer cylinder remains fixed. Ribs attached to the outer cylinder prevent slip. The rotation speed of the inner spindle is reduced from an initial maximum value in a stepwise fashion. The torque required to turn the spindle is considered the sum of the torque in the annulus (area between the outer and inner cylinders) and the torque in the space under the bottom of the spindle. The torque in the annulus and in the space below the spindle can be described with equations for coaxial cylinders rheometers and parallel plate rheometers, respectively. From these equations the yield stress and plastic viscosity can be calculated in fundamental units. The device is calibrated using a fluid of known flow properties. Yen et al. (1999) used malt sugar with known properties, as measured with an established traditional coaxial cylinder viscometer.

The geometry of the FHPCM is problematic. The ratio of the outer cylinder radius to the inner cylinder radius is 1.51. The maximum aggregate size that can be tested, based on the maximum aggregate size being 1/5 the distance between the outer and inner cylinders, is 7.6 mm. In research (Yen et al. 1999) conducted using the FHPCM, the maximum size of aggregate used was 12.7 mm.

The rheometer, which is considered appropriate only for highly flowable concretes, has been used successfully for concretes with slumps of 140 mm to 280 mm.

Advantages:
- The device measures yield stress and plastic viscosity for highly flowable concretes.
- The operation of the device is automated.

Disadvantages:
- The device was developed for research and has not been verified with extensive laboratory testing.
- The device is only appropriate for highly flowable concretes.
- Based on general principles of coaxial cylinders rheometers, the geometry of the FHPCM is problematic.
- The device is too large for field use.

3.1.4.8   CEMAGREF-IMG

The CEMAGREF-IMG (Ferraris and Brower 2001) is a large coaxial-cylinders rheometer originally developed to measure mud-flow rheology, but which has also been used to measure concrete rheology. Only one prototype of the device exists.

Since the CEMAGREF-IMG was not initially intended to measure the rheology of concrete, it is significantly larger than other rheometers. In fact, the large size of the device makes it impractical for measuring concrete. The outer cylinder is 120 cm in diameter and 90 cm tall, while the inner cylinder is 76 cm in diameter. The rheometer holds 500 liters of concrete and is mounted on a trailer. The inner cylinder rotates and measures torque while the outer cylinder remains stationary. Blades on the outer cylinder and a metallic grid on the inner cylinder reduce concrete slippage. Since the inner cylinder is mounted within the outer cylinder from the bottom instead of from the top, a rubber seal is provided at the base of the inner cylinder to ensure that all concrete remains within the gap between the cylinders. The torque on the inner cylinder at various rotation speeds is logged and used to calculate yield stress and plastic viscosity.

Although the large dimensions of the CEMAGREF-IMG allow the testing of concrete mixtures with large maximum aggregate sizes, the ratio of the outer radius to the inner radius is too large. As a result, plug flow occurs as the concrete near the inner cylinder is sheared while the shear stress applied to the concrete near the outer cylinder is insufficient to overcome the yield stress of the concrete. The large size of the CEMAGREF-IMG also makes the device impractical to transport.

Advantages:
- The device measures yield stress and plastic viscosity.
- The size of the device accommodates large maximum aggregate sizes.

Disadvantages:
- The device was not originally designed to measure concrete and is too large for common field use.
- The geometry of the device should be improved to more accurately measure concrete rheology.
- The seals at the bottom of the inner cylinder must be replaced periodically and must be accounted for in the device's calibration.

3.1.4.9   Soil Direct Shear Test

The direct shear test used for soil (Powers 1968) can be performed with fresh concrete to assess the cohesive strength of a concrete mixture. The results of the test are given in terms of soil mechanics parameters, not in terms of yield stress and plastic viscosity.

The device, as described by Powers (1968), consists of a ring shaped container filled with compacted concrete. The lower half of the device is held in a fixed position while the upper half of the device is rotated slowly, resulting in a maximum shear stress on the plane between the two halves of the container. A vertical load can be applied to the concrete during the test. The test

measures the angle of rotation of the upper container and the corresponding torque required to turn the container.

A typical plot of torque versus relative displacement shows an initial linear increase in torque up to a maximum value and then a decline followed by a gradual leveling off of the curve. The maximum stress is considered the "static friction" and the stress after the plot has leveled off is considered the "sliding friction." The linear relationship between static friction and normal stress allows the calculation of the angle of internal friction.

Advantages:
- The test essentially determines the yield stress of the concrete.
- The test provides additional information, namely the angle of internal friction, not available from most conventional tests.

Disadvantages:
- The results of the test are not described in terms of shear stress and shear rate. The use of the direct shear test predates the establishment of concrete as a Bingham material. The additional information provided by the test is not necessarily useful.
- The test does not provide a measure of plastic viscosity.
- The test is strictly a laboratory device.

3.1.4.10 Mixer Devices

Multiple devices have been developed to measure the consistency of concrete while still in a mixer. Although the testing principle and apparatus vary for each test method, the general objective of each test method is to measure continuously the consistency or slump of concrete before it is discharged from the concrete mixer. Such devices that have been patented in the United States are listed in Table 6. Although the test methods resemble rotational rheometers, they typically only measure a value related to slump, not yield stress and plastic viscosity.

As Table 6 indicates, the devices to measure the workability of concrete in a mixer have been developed over a nearly seventy-year period. One of the most recent devices, the ready mix truck hydraulic device (US patent 4,356,723; Wong et al. 2000) measures the torque required to turn the mixer on a ready mix truck and correlates this torque reading to slump. Since each truck can be different, correlations must be developed for each truck to account for differences in mixer geometries and other characteristics. The results could also be influenced by the quantity of concrete in the truck and the density of the concrete.

A separate but similar device called a plastograph (Wong et al. 2000) was used by the US Army Corp of Engineers. The device measures the flow of concrete in a concrete mixer, which is then related to slump.

50

Table 6: US Patented Devices to Measure Workability of Concrete in Mixer

Patent Number	Date Issued	Patent Title
1,730,893	Oct 8, 1929	Method of and apparatus for determining consistency of concrete
1,898,890	Feb 21, 1933	Concrete mixometer
1,980,184	Nov 13, 1934	Control recording apparatus
2,013,837	Sept 10, 1935	Consistency and time indicating and recording equipment for concrete mixers
2,409,014	Oct 8, 1948	Mix consistency indicator for concrete mixers
2,629,790	Feb 24, 1953	Apparatus for measuring and/or controlling the consistency of a paste or slurry
2,643,542	Jun 30, 1953	Apparatus for determining consistency of concrete mix
2,821,079	Jan 28, 1958	Apparatus for measuring the consistency during mixing of concrete
3,237,437	Mar 1, 1966	Slump meter
3,403,546	Oct 1, 1968	Slump indicator for concrete
3,631,712	Jan 4, 1972	Method and apparatus for determining slump in concrete
3,640,121	Feb 8, 1972	Slump indicator
3,924,447	Dec 9, 1975	Slump indicator
4,356,723	Nov 2, 1982	Process and apparatus for continuously measuring slump
4,900,154	Feb 13, 1990	Concrete mixer having means for determining consistency of concrete mixing therein
6,227,039	May 8, 2001	System and method for controlling concrete production

Advantages:
- Concrete consistency can be measured continuously while concrete is still in the mixer prior to discharge.
- Unlike the delivery-chute meters, the devices that measure consistency of concrete in the mixer do not require concrete to be discharged onto a delivery chute.

Disadvantages:
- The test devices described in the patent documents listed in Table 6 typically only measure consistency.
- All of the devices must be calibrated to determine consistency.
- Differences in mixer characteristics must be considered in using any device.
- The devices measure workability of an entire concrete sample and cannot detect variations in workability within a concrete sample.

3.1.4.11 Fresh Concrete Tester (FCT 101)

Several European companies sell a hand-held impeller-type device (Steiner 1996; Wong et al. 2000), marketed under various trade names, to measure the consistency of concrete in place. Wong et al. (2000) evaluated the feasibility of using a Colebrand tester. At least two UK companies sell the Fresh Concrete Tester, FCT 101.

The test device resembles a hand-held version of the Tattersall two-point test or the IBB rheometer. The device, which is battery operated, is approximately the size of a drill and includes an impeller with two small hemispheres that is inserted into fresh concrete. An electronic interface records the torque required to turn the impeller. The device can also be fitted with a temperature probe. The device must be calibrated for each particular concrete mixture in order to correlate torque readings to slump, water/cement ratio, and predicted compressive strength. According to product literature, the FCT 101 test can be performed in 2 minutes. This rapid testing speed allows concrete essentially to be tested continuously in order to monitor the stiffening of concrete and the loss of water over time. The readings made by the device are logged and can be downloaded to a computer for documentation.

Although the Tattersall two-point test and the IBB rheometer measure parameters directly related to both yield stress and plastic viscosity, the FCT 101 only measures a value of consistency that is correlated to slump. According to Wong et al. (2000), the device appears to use signal averaging to minimize the variability caused by large aggregates. The device does not operate at multiple shear rates. The rotating hemispheres tend to create channels within low and moderate slump concretes, making it difficult to measure the plastic viscosity by using multiple shear rates at one location in the concrete sample. The H-shaped impellers on the Tattersall two-point device and on the IBB rheometer move in a planetary motion to help avoid this problem.

Advantages:
- The device allows for fast and continuous measurement of workability.
- The embedded electronic interface allows for the instant correlation of test readings to slump and water content and for the prediction of compressive strength. The results can be logged for documentation purposes.

Disadvantages:
- Although the impeller design of the device resembles more advanced rheometers, the device only measures consistency and not plastic viscosity.
- The device must be calibrated for each concrete mix. Each calibration is only valid for one particular concrete mix.
- The impeller could create a continuous channel in stiff concretes. The resulting torque measurements would suggest an artificially high consistency reading.

3.1.5   Test Methods for Very Low Slump Concrete

Very low slump concretes are typically too stiff to be measured with test methods that consider the ability of concrete to flow. Instead, tests for very low slump concretes generally attempt to simulate the actual placement conditions for low slump concretes and measure more relevant properties like compactability. The proctor test and the Kango hammer test utilize vibration to compact samples whereas the intensive compaction test uses compression and shear forces. These tests are generally simple to perform, although none can be used as a simple field quality control device.

3.1.5.1 Proctor Test

The proctor test used for soils can also be used for lean, dry concrete mixes (Juvas 1994; Bartos, Sonebi, and Tamimi 2002). The test procedure for concrete is the same test procedure commonly used for soils. Either the standard Proctor test (ASTM D698) or the modified Proctor test (ASTM D1557) can be used. Four to six samples, each with varying moisture content, are compacted in a cylindrical mold using a drop hammer. The unit weight of each compacted sample is plotted against moisture content to determine the maximum dry unit weight and corresponding moisture content.

In its guidelines for developing mix proportions for low slump concretes, ACI Committee 211 (2002) recommends using the proctor test.

Advantages:
- The test is appropriate for low slump concrete mixtures that cannot be tested with conventional workability tests.
- The test is simple and well known.

Disadvantages:
- The test does not incorporate vibration, which is commonly used to compact low slump concretes.
- The test is time consuming: performing the test requires four to six samples to be prepared to define the unit weight versus moisture content curve.

3.1.5.2 Kango Hammer Test

The Kango hammer test (Juvas 1994; Bartos, Sonebi, and Tamimi 2002) attempts to measure workability by simulating the effect of vibration and pressing on low-slump concretes. The test is based on British standards BS1924:1975, "Methods of test for stabilized soils," and BS 1377:1975, "Vibrating hammer method". Concrete is placed in a cubic or cylinder mold in two to three separate layers. A demolition hammer, which is mounted in a frame and equipped with a special bit that fits the shape of the mold, applies a constant pressure and vibration to each layer of concrete. After compaction of all layers, the density of the concrete specimen is determined. The greater the density of the compacted concrete specimen, the greater will be the compactability and workability of the concrete mix.

The particular demolition hammer typically used for this test method is manufactured by Kango Tools of Winnenden, Germany. Bartos, Sonebi, and Tamimi (2002) recommend using a model 900 or 950.

Advantages:
- By using both vibration and pressure, the test accurately simulates field placement conditions.
- The test is simple and easy to perform.

Disadvantages:
- The particular hammer is not specified, making comparisons of the test results difficult.
- The apparatus is larger than the proctor test and requires electricity.

3.1.5.3 Intensive Compaction Test

The intensive compaction test (Juvas 1990; Tattersall 1991; Juvas 1994; US patent 4,794,799; US patent 4,930,346) is a gyratory compactor used to measure the workability of concrete mixtures with slumps less than approximately 1 cm. The test device—which is used for quality control, mix proportioning, and research—has been standardized in Nordtest-Build 427, ISSN 0283-7153.

The test apparatus is a machine that applies compression and shear forces to a concrete specimen while recording the density of the specimen. To perform the test, the concrete to be tested is placed in a cylindrical mold, which is loaded into the test apparatus. The mold is available in two diameters—a 100 mm diameter mold is used for concretes with maximum aggregate sizes of up to 20 mm while a 150 mm diameter mold is appropriate for maximum aggregate sizes up to 32 mm. Two pistons at either end of the cylinder apply a compressive force to the sample. Simultaneously, the angle of inclination of the pistons rotates to apply a shearing motion to the concrete. This compaction technique is represented in Figure 21. The pressure and speed of rotation can be adjusted for each test; however, these variables are held constant during each test. The volume of the sample, which is used to calculate density, is recorded continuously throughout the test. The test is performed in 3-5 minutes.
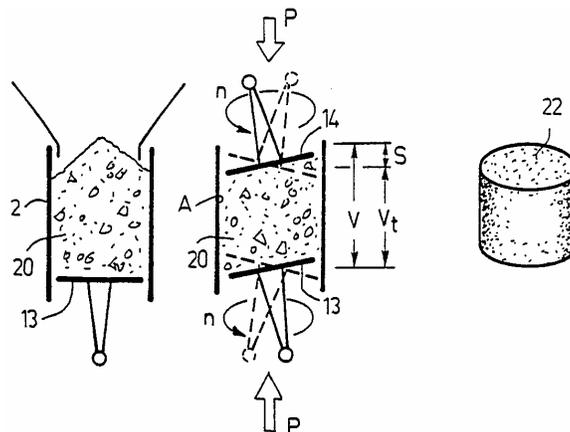
Figure 21: Compaction of Concrete Sample in Intensive Compaction Device (US Patent 4,794,799)

To determine the workability of a concrete mixture, the density of the concrete is plotted versus the number of working cycles of the pistons. Concrete mixes are evaluated by comparing the density after a certain number of cycles under a given pressure. Additionally, the performance of concrete production machines can be evaluated by comparing the density achieved with a particular machine to the density achieved with the intensive compaction test.

After the test, the sample of concrete can be removed from the cylinder mold and tested for compressive or splitting tensile strength either in the concrete's fresh or hardened state. The results of the intensive compaction test show good correlation to the results of the Kango hammer test and the Proctor test.

Although the larger 150 mm diameter model is too heavy and bulky for field use, the lightweight version of the 100 mm diameter model weighs approximately 120 lbs and can be transported to a field site. Electricity and compressed air are required to perform the test.

Advantages:
- Research has shown that the test is capable of accurately measuring even small changes in mixture proportions.
- The test accurately simulates placement conditions for low slump roller-compacted concretes.
- The test is fast and computer controlled.
- The test can be used for research, mix proportioning, or quality control. The smaller 100 mm model is feasible for field use.

Disadvantages:
- The equipment is expensive, especially when compared to the proctor test. The 150 mm diameter model is too heavy for field use.
- The test does not incorporate vibration, which is commonly used in the placement of low slump concrete.

3.1.6   Other Test Methods

Several workability tests methods do not fit into the NIST classification scheme. Although these tests can provide useful information about the workability of concrete, they do not incorporate the conventional approaches encompassed by the NIST classification scheme.

3.1.6.1   Trowel Test

The trowel test (Bartos 1992; Dobrowlski 1998; Bartos, Sonebi, and Tamimi 2002) is a non-standard, subjective test to characterize the cohesiveness of a concrete mix. As a sample of concrete is troweled, the cohesiveness of the mix is judged by observing how well the concrete sticks together and whether the concrete sticks to the trowel. After the sample has been troweled, the magnitude of bleeding is observed subjectively. The test, when preformed by an experienced operator, can determine whether a given concrete mixture has a sufficient amount of mortar. Harsh mixes are difficult to trowel. The number of passes made by a trowel in order to bring the cement paste to the surface of the concrete can be used as an indication of workability. The test is most appropriate in situations when it is used in addition to other standard tests.

Advantages:
- The test is simple and inexpensive.
- When performed by an experience operator, the test can provide more information on workability than other tests. The subjective comments from the trowel test can have greater useful meaning than objective numbers from other tests.

Disadvantages:
- The test is subjective, providing no numerical results.
- As a subjective test, the trowel test cannot be used in specifications.

- While the test does simulate concrete finishing, it does not simulate other placement conditions.

3.1.6.2 Multiple Single-Point Tests

Instead of using one single-point test to measure workability, multiple single-point tests can be performed. For instance, ACI 309.1R-93 describes the use of four tests—namely, for harshness, segregation resistance, shear resistance, and stickiness—to better characterize workability. Each test is considered at least partially independent of the other tests. Harshness is measured as the spread of concrete on a flow table; segregation resistance is measured as the amount of mortar separated from concrete by jolting a flow table; shear resistance is measured using the shear box developed by Terzaghi and Casagrande for soils; and stickiness is measured as the vertical force required separating a steel plate from concrete.

Advantages:
- The four tests give more information about a given concrete mix than one single-point test.
- Each test is simple and inexpensive to perform.

Disadvantages:
- Conducting multiple tests requires additional time and cost.
- The tests do not directly measure yield stress and plastic viscosity.

3.1.6.3 Soil Triaxial Test

The soil triaxial test (Ritchie 1962; Powers 1968) can be used to measure the resistance of concrete to shear stress. The test is conducted with the same apparatus and with the same procedure as the triaxial test commonly used for soils. The results of the triaxial test are plotted on a Mohr diagram, which relates shear stress to normal stress. Based on the Mohr diagram, the Mohr envelope can be constructed in order to determine the maximum shear stress and corresponding normal stress at failure and the angle of internal friction. The test has been conducted on concrete mixtures with slumps ranging from 2 to 5 inches.

Advantages:
- Like the direct shear test, the triaxial test provides additional information about concrete.
- The test can be used for low slump concretes.

Disadvantages:
- The test does not measure workability in terms of shear stress and shear rate. The additional information provided by the test is not necessarily useful.
- The test is expensive and not appropriate for field use.

3.1.6.4 System and Method for Controlling Concrete Production

A system to monitor and control the quality of concrete throughout production based on rheological properties was recently developed and patented (US patent 6,227,039). The system consists of multiple test devices that measure rheological properties of concrete at various stages of concrete mixture proportioning, production, transport, and placement. Each device is used as

appropriate; not all devices are used for a given concrete mix. At a minimum, testing is conducted during the mix proportioning process, at the concrete plant during concrete batching and mixing, and away from the concrete plant (either at the jobsite or during transit).

The first device described in the patent document consists of an inverted U-shaped box mounted within a rigid frame, as shown in Figure 22. The entire device is submerged in a sample of fresh concrete. A piston, designated as 42, moves up and down to force fresh concrete in and out of the box. Multiple stress and pressure sensors throughout the device monitor the forces generated in the test device and in the concrete. To measure the effect of vibration on the concrete, a vibrator (12) can be used. A data collection system logs data from all sensors for further analysis. The patent document suggests two methods to measure workability with this device: by determining the time required for the test device to produce a given deformation under a constant force or by determining the resistance to shear at a given rate of deformation.
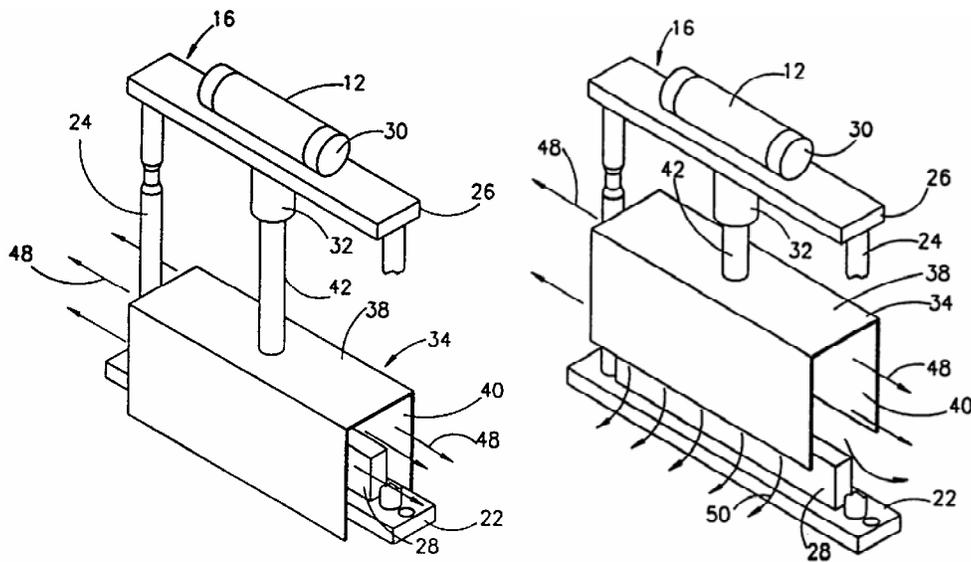
Figure 22: First Test Device in Concrete Production Control System (US Patent 6,227,039)

The second embodiment of the test device is shown in Figure 23. The U-shaped portion of the box is immersed in a sample of concrete. The rotation of the paddle, forces concrete upwards in the box and against stress sensors (132). A tachometer and an ammeter measure the performance of the electric motor. As before, the data from the device is sent to a data collection system for further analysis.
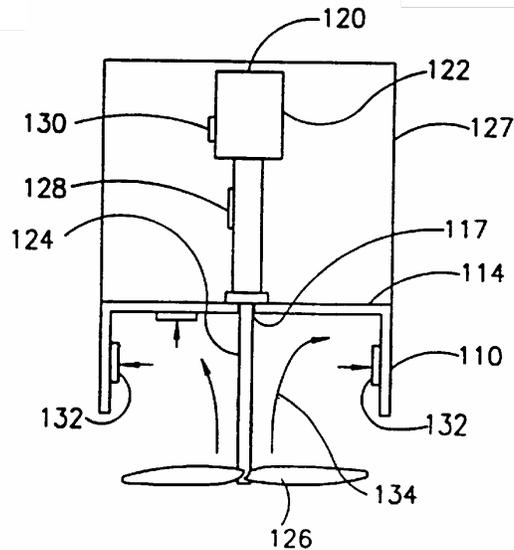
Figure 23: Second Test Device in Concrete Production Control System (US Patent 6,227,039)

A third test device measures the performance of concrete pumps in order to quantify workability. For pumps consisting of a screw-type device, an ammeter measures the current used by the pump and a tachometer measures the speed of rotation of the screw. For piston-type hydraulic pumps, a manometer measures the changing hydraulic pressure in the pump and an electronic ruler measures the displacement of the piston. After concrete leaves the hopper, additional sensors mounted to the inside of the exit pipe measure changes in pressure as concrete flows through the pipe.

The fourth test device, which is applicable to pumped concretes, is essentially a venturi meter. The diameter of a pipe in a pumping system is narrowed. Pressure sensors monitor the changing stress states as the concrete moves through the narrowed section of the pipe. The patent document does not indicate how this data is used.

The fifth test device described in the patent document consists of a flexible strip inserted into a 90 degree pipe bend within a pumping system. Sensors mounted to the flexible strip measure the loss in pressure and the change in stress states as the concrete moves through the bend.

To measure concrete at different stages of concrete production further, the patent document suggests that previously described devices, shown in Figure 22 and Figure 23, can be used in stationary paddle mixers and mobile ready-mix trucks.

A final system described in the patent document applies to the production of concrete blocks. Under the described system, blocks are randomly selected from a production line and measured for size and mass. The fresh concrete compressive strength of each block is measured. The rheology of the mix can be measured using the first device described in the patent document, shown in Figure 22. It is not clear that this particular device is applicable to low and zero slump concrete mixtures typically used in the casting of concrete blocks.

The output of each test device is used to create a "rheological profile" of the concrete mixture. Unlike other devices that relate shear stress to shear rate, the "rheological profile" generated in accordance with the patent document relates shear stress to shear deformation. No dimensions for any of the devices are provided in the patent document. Each device in the patent document is described with progressively less detail.

It must be noted that the patent claims to cover not just the test devices but also the system for monitoring workability from mix proportioning to concrete placement. The system begins with the mix design process. Multiple mixes are prepared in order to develop a mix with desired rheological properties. At the concrete plant and in the field, the concrete batch can be modified as necessary until the rheological parameters of the mix match the desired design properties.

An initial patent (US patent 5,948,970) was granted in 1999 and a continuation of the original patent was granted in 2001. At the time of this writing, it is not known whether this system is sold commercially.

Advantages:
- The system monitors the rheology of concrete throughout the production process.
- Mixture designs and later changes to mix designs can be made to optimize rheology and hardened concrete properties and to minimize costs.

Disadvantages:
- Although the system allows rheology to be measured throughout production, different devices are used. The results from one device should generally not be directly compared to the results of other test devices.
- The devices typically measure shear stress versus shear deformation to develop a rheological profile, instead of the more conventional relationship between shear stress and shear rate.
- The devices used in the system appear to be appropriate only for concretes with moderate to high slumps.

3.2 Workability Test Methods for Self-Compacting Concrete

Self-compacting concrete (also self-leveling, super workable, or self-consolidating concrete) presents new challenges for the measurement of workability. Since self-compacting concrete is capable of flowing readily under its own weight, its yield value is near zero. Therefore, in measuring the workability of self-compacting concrete, yield stress is a less important parameter than it is for conventional concrete. Although the yield stress of self-compacting concrete is still evaluated, other properties related to plastic viscosity and segregation resistance must also be examined.

Since, at the time of this writing, self-compacting concrete remains a nascent technology with limited widespread use, particularly in the Unites States, no tests have been formally standardized, although several tests are finding widespread use. Since there is generally no agreement on dimensions and materials for the devices described below, the tests cannot be

easily specified. It must be noted here that self-compacting concrete, in contrast to conventional concrete, is a proprietary, engineered product and not a commodity product. As such, it is more likely to be the subject of performance-based specifications. Researchers studying the use self-compacting concrete have developed laboratory tests to understand more fully the movement and consolidation of self-compacting concrete. Such laboratory experiments, like the one presented by Tanaka et al. (1993), are typically intended solely for research and are not reported in this document.

Workability tests for self-compacting concrete can be broadly split into three categories: filling ability tests, passing ability tests, and segregation resistance tests. Each test described below fits into one or more of these categories. In accordance with the NIST classification scheme, the tests for self-compacting concrete typically fit into the confined flow and free flow test categories. As previously discussed, many rotational rheometers are capable of measuring self-compacting concrete. In addition to the test methods described below, the free orifice (orimet) test can be used for self-compacting concrete.

3.2.1   V-Funnel Test

The V-funnel test (EFNARC 2002; Bartos, Sonebi, and Tamimi 2002) is used to measure the filling ability of self-compacting concrete and can also be used to judge segregation resistance. The test method is similar to the concept of the flow cone test used for cement paste.

The test apparatus, shown in Figure 24 consists of a V-shaped funnel with a height of 425 mm, a top width of 490 mm, a bottom width of 65 mm, and a thickness of 75 mm. At the bottom of the V-shape, a rectangular section extends downward 150 mm. Alternatively, an O-shaped funnel with circular cross section can be used. The entire funnel is filled with concrete without tamping or vibration. The door at the bottom of the funnel is opened and concrete is allowed to flow out of the funnel and into a bucket. The flow time for all of the concrete to exit the funnel is recoded as a measure of filling ability. For self-compacting concrete, the flow time should be less than 10 seconds. To measure segregation resistance, the V-funnel is refilled with concrete and allowed to sit for 5 minutes. The door is again opened and the flow time is recorded. The greater the increase in flow time after the concrete has remained at rest for five minutes, the greater will be the concrete's susceptibility to segregation. Further, non-uniform flow of concrete from the funnel suggests a lack of segregation resistance.
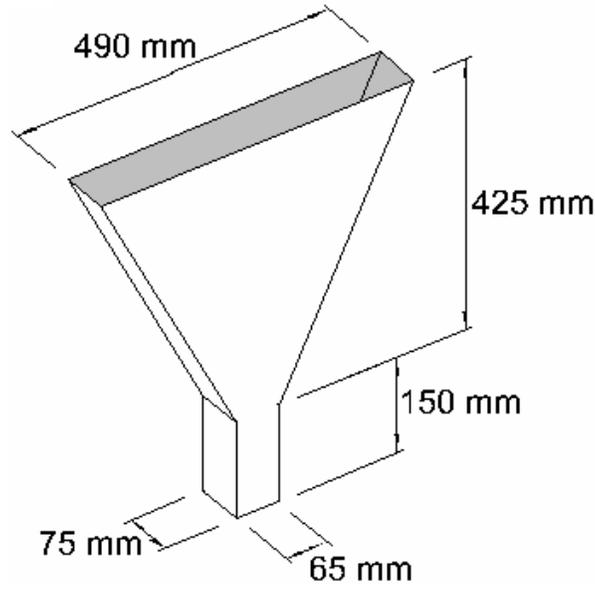
Figure 24: V-Funnel Test Apparatus

The average flow through speed, V_m, is calculated in terms of the flow through time, t_0;

$$V_m = \frac{0.01}{(0.065 \times 0.075) \times t_0} = \frac{2.05}{t_0}(m/s)$$ [14]

To quantify segregation resistance, the flow-through index, S_f, is calculated in terms of initial flow through time, t_0, and the flow through time after 5 minutes, t_5:

$$S_f = \frac{t_5 - t_0}{t_0}$$ [15]

3.2.2 Slump Flow Test

The simplest and most widely used test method for self-compacting concrete is the slump flow test (Kuroiwa et al. 1993; EFNARC 2002; Bartos, Sonebi, and Tamimi 2002). The test, which was developed in Japan, was originally used to measure underwater concrete and has also been used to measure highly flowable concretes.

To perform the test, a conventional slump cone is placed on a rigid, non-absorbent plate and filled with concrete without tamping. The plate must be placed on a firm, level surface. The slump cone is lifted and the horizontal spread of the concrete is measured. For an additional measure of flowability, the time required for the concrete to spread to a diameter of 50 cm can be measured. This value of T_{50} generally ranges from 2-7 seconds.

It is possible to assess the stability of concrete qualitatively after performing the slump flow test. A visual stability index (VSI) has been developed as a standard means of determining stability. A numerical score—on a scale of 0 to 3—is assigned based on a visual evaluation of the

segregation and bleeding in the concrete sample. Self-compacting concrete should exhibit a rating of 0 or 1 to be considered acceptable.

3.2.3 J-Ring Test

The J-ring test (EFNARC 2002; Bartos, Sonebi, and Tamimi 2002) extends common filling ability test methods to also characterize passing ability.

The J-ring test device can be used with the slump flow test, the orimet test, or the V-funnel test. The J-ring, as shown in Figure 25, is a rectangular section (30 mm by 25 mm) open steel ring with a 300 mm diameter. Vertical holes drilled in the ring allow standard reinforcing bars to be attached to the ring. Each reinforcing bar is 100 mm long. The spacing of the bars is adjustable, although 3 times the maximum aggregate size is typically recommended. For fiber-reinforced concrete, the bars should be placed 1 to 3 times the maximum fiber length.
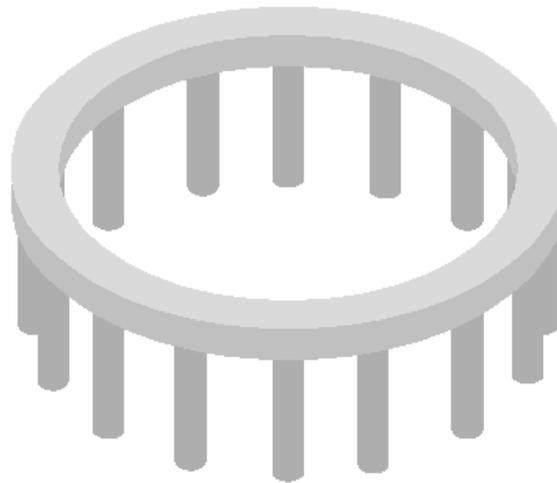
Figure 25: J-Ring Test Apparatus

To conduct the J-ring test in conjunction with the slump flow test, the slump cone is placed in the center of the J-ring and filled with concrete. The slump cone is lifted and concrete is allowed to spread horizontally through the gaps between the bars. Alternatively, the orimet device or the V-funnel can be positioned above center of the J-ring. Instead of measuring just the time for concrete to exit the orimet or the V-funnel, the concrete is also allowed to spread horizontally through the J-ring.

Various interpretations of the test results have been suggested. The measures of passing ability and filling ability are not independent. To characterize filling ability and passing ability, the horizontal spread of the concrete sample is measured after the concrete passes through the gaps in the bars of the J-ring and comes to rest. Also, the difference in height of the concrete just inside the bars and just outside the bars is measured at four locations. The smaller this difference in heights is, the greater the passing ability of the concrete will be. Alternatively, the horizontal spread with and without the J-ring can be compared as a measure of passing ability.

3.2.4   L-Box Test

The L-box test (EFNARC 2002; Bartos, Sonebi, and Tamimi 2002) measures the filling and passing ability of self-compacting concrete. Originally developed in Japan for underwater concrete, the test is also applicable for highly flowable concrete.

As the test name implies, the apparatus consists of an L-shaped box, shown in Figure 26. Concrete is initially placed in the vertical portion of the box, which measures 600 mm in height and 100 mm by 200 mm in section. A door between the vertical or horizontal portions of the box is opened and the concrete is allowed to flow through a line of vertical reinforcing bars and into the 700 mm long, 200 mm wide, and 150 mm tall horizontal portion of the box. In the most common arrangement of reinforcing bars, three 12 mm bars are spaced with a clear spacing of 35 mm. Generally, the spacing of the reinforcing bars should be three times the maximum aggregate size. It should be noted that various dimensions for the L-box have been used and no one set of dimensions is considered official; however, the dimensions described above seem to be the most common.
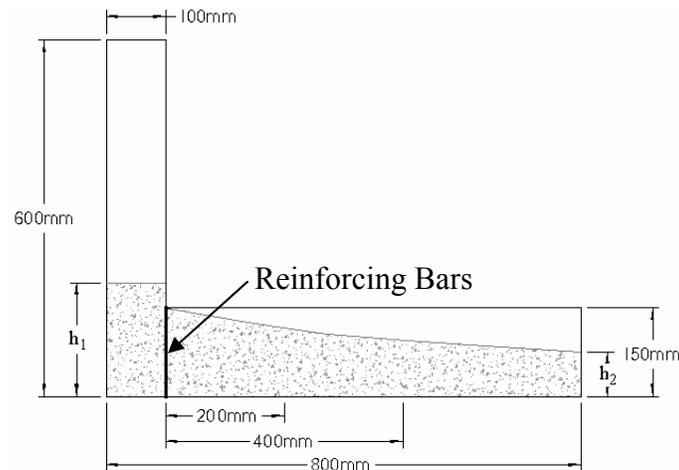
Figure 26: L-Box Test Apparatus

The time for concrete to reach points 20 cm (T_{20}) and 40 cm (T_{40}) down the horizontal portion of the box is recorded. After the concrete comes to rest in the apparatus, the heights of the concrete at the end of the horizontal portion, H_2, and in the vertical section, H_1, are measured. The blocking ratio, H_2/H_1, for most tests should be 0.80 to 0.85. If the concrete being tested is truly self-leveling, like water, the value of the blocking ratio will be unity. Segregation resistance can be evaluated visually. A concrete sample with coarse aggregate particles that reach the far end of the horizontal part of the box exhibits good resistance to segregation. The L-box can be disassembled after the concrete has hardened. By cutting out samples of the hardened concrete, additional information about the concrete's resistance to segregation can be determined, as shown by Tanaka et al. (1993).

While the test does give valuable information about filling and passing ability, and to a lesser extent, segregation resistance, the test is not as simple as the slump flow test. Since there are no standardized dimensions, results from different test apparatuses cannot be compared directly.

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3.2.5 U-Box Test

The U-box test (Kuriowa 1993; EFNARC 2002; Bartos, Sonebi, and Tamimi 2002) measures filling ability and is similar to the L-box test. The U-box test was developed in Japan and is sometimes referred to as the box-shaped test. Like other workability tests for self-compacting concrete, the U-box test is also applicable to highly flowable concretes and underwater concretes.

The apparatus consists of a U-shaped box, as shown in Figure 27. Concrete is placed in the left side of the box. An alternative version of the apparatus features a flat bottom instead of a curved bottom. Ideally, the box should be made of clear plastic to permit the observation of the concrete in the box. To start the test, the door dividing the two halves of the box is opened and concrete is allowed to flow from the left half of the box into the right half. Reinforcing bars are placed at the location of the door. Although the spacing of the bars is adjustable, the most common arrangement is 13 mm diameter bars with a clear spacing of 35 mm. The time from the opening of the door until the concrete ceases to flow is recorded. The height of the concrete in each side of the box is measured. A truly self-leveling fluid will rise to the same height on each side of the box. Concrete with good filling ability should reach a height of at least 30 cm on the right side of the box. In some versions of the test, a surcharge load is applied to the concrete on the left side of the box. This surcharge load is unnecessary for self-compacting concrete and is generally not used.

With both the L-box and U-box tests, it is unknown what significance the effect of friction between the concrete and the walls has on the test results.
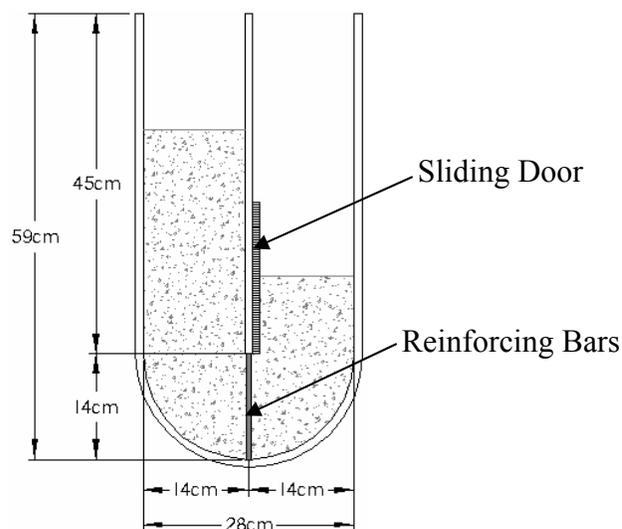

Figure 27: U-Box Test Apparatus

3.2.6 Fill Box Test (Simulated Filling Test, Filling Capacity Box, Kajima Test)

The fill box test (EFNARC 2002; Bartos, Sonebi, and Tamimi 2002) measures the passing ability and segregation resistance of self-compacting concrete.

The apparatus consists of a clear plastic box with 35 plastic 20 mm diameter bars, as shown in Figure 28. An early version of the test featured a wedge shaped box instead of a rectangular box and did not include a funnel. Concrete is poured at a constant rate into the funnel and allowed to flow into the box until the height of the concrete reaches the height of the top row of bars. After the concrete comes to rest, the height of the concrete at the two ends of the box is measured.
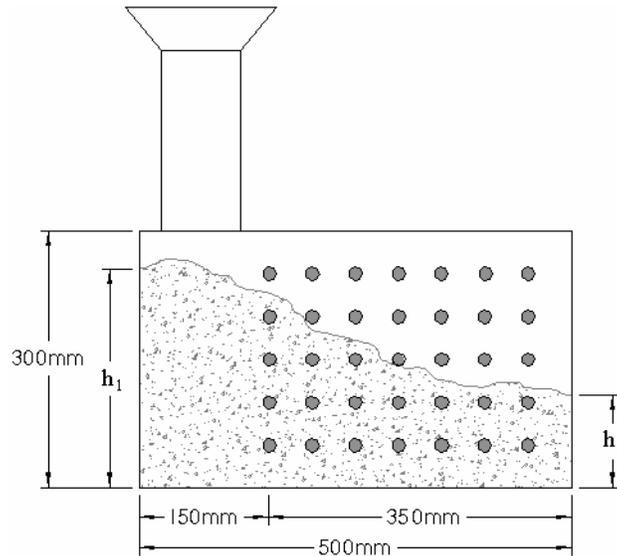
Figure 28: Fill Box Test Apparatus

These measurements of the height of the concrete at the side nearest the funnel, h_1, and the height at the opposite end, h_2, are used to calculate the average filling percentage:

$$\text{Filling Percentage} = \frac{(h_1 + h_2)}{2h_1} \cdot 100\% \qquad [16]$$

The closer the filling percentage is to 100%, the greater the filling ability of the concrete.

The test is a good representation of actual placement conditions. However, the test is bulky and difficult to perform on site.

A similar simulated soffit test (Bartos, Sonebi, and Tamimi 2002) consists of a rectangular box with reinforcing bars placed in the box in an arrangement that simulates actual placement conditions for a given job. The reinforcing bars can be both horizontal and vertical. Concrete is placed in the box in a similar manner as with the simulated filling apparatus. After the concrete is allowed to harden, saw-cut sections of hardened concrete are removed to judge how well the concrete filled the box and moved around reinforcing bars. Since each apparatus is constructed based on actual field conditions, the test is not standardized and results from different apparatuses cannot be directly compared.

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3.2.7 Wet Sieving Stability Test (GTM Screen Stability Test)

The wet sieving stability test (EFNARC 2002; Bartos, Sonebi, and Tamimi 2002) was developed by a French contractor to measure the segregation resistance of self-compacting concrete.

To perform the test, a 10 liter sample of concrete is placed inside a bucket and allowed to sit for 15 minutes to allow any internal segregation to occur. The container is sealed to prevent evaporation. After sitting for 15 minutes, the top approximately 2 liters of the concrete is poured from the bucket into a smaller pouring container. This 2 liter sample of concrete is then poured from a height of 500 mm onto a 5 mm sieve. Mortar from the sample is allowed to flow through the sieve into a lower sieve pan for a period of 2 minutes. The mass of the concrete poured onto the sieve, M_a, and the mass of mortar in the sieve pan, M_b, are measured and used to calculate the segregation ratio:

$$\text{Segregation Ratio} = \frac{M_b}{M_a} \cdot 100\% \qquad [17]$$

The segregation ratio should be between 5-15% for acceptable segregation resistance. Concretes with a segregation ratio above 15% will exhibit too much segregation. Severe segregation is suspected if the segregation ratio is above 30%. If the segregation ratio is less than 5%, the sample is too harsh and will result in a poor surface finish.

Although the test results are valuable and accurate, the test is slow and requires an accurate scale, making it unsuitable for field use. Additionally, poor repeatability of the test results has been reported.

3.2.8 Penetration Test for Segregation

The penetration test for segregation (Bartos, Sonebi, and Tamimi 2002; Bui, Akkaya, and Shah 2002) measures the penetration resistance of highly fluid and self-compacting concretes.

The test apparatus consists of a hollow cylindrical penetration head that is allowed to sink under its own weight into a sample of concrete. The penetration head has an inside diameter of 75 mm, a thickness of 1 mm, and a height of 50 mm. The mass of the penetration head is 56 grams. A rod attached to the penetration head slides through a frame, which includes a graduated scale for measuring penetration depth. Several different dimensions for the concrete container have been used by different researchers. Bui, Akkaya, and Shah (2002) set the apparatus on top of an L-box with cross sectional dimensions of 200 mm by 200 mm (instead of the more commonly used dimensions of 100 mm by 200 mm). The container must be placed on level ground and must not be moved during the test. The concrete, which is not consolidated with vibration or tamping, is allowed to sit for two minutes after being placed into the container. The cylinder is then placed on top of the concrete surface and the depth of penetration is measured after 45 seconds. This measurement is performed at a total of three different locations of the concrete surface. When the concrete mixture is susceptible to segregation, the coarse aggregate particles will settle from

the top surface of the concrete and the penetration depth will increase. If the average depth of penetration is greater than 8 mm, the concrete is considered to have poor segregation resistance.

The test method is simple and inexpensive; however, little data exists to relate test results to actual field performance.

3.3   Workability Test Methods for Pastes and Grouts

Test devices with varying degrees of complexity are available to measure the rheology of cement pastes and grouts. These devices typically use similar principles as devices used to measure concrete, but usually feature smaller dimensions. In fact, some concrete rheometers have smaller versions available for measuring mortar.

The rheology of cement paste is frequently measured during research to determine the effects of chemical admixtures on cement paste rheology. Since, in many cases, cement paste can be measured more easily and accurately than concrete, the results of cement paste testing are more significant. Changes in cement paste rheology can be correlated to concrete rheology.

3.3.1   Flow Cone Test

Several versions of a funnel test are used to measure the workability of pastes and grouts. These devices differ in dimensions and intended uses; however, they all work on the principle of measuring the time for fresh paste or grout to flow through the opening of a funnel.

The flow cone test (Scanlon 1994) is intended for use in measuring the flow properties of grout for preplaced-aggregate concrete, but can also be used for other highly flowable grouts. The test is standardized in ASTM C939 and is considered appropriate for use in both the field and the lab. To perform the test, grout is poured into the flow cone, which is shown in Figure 29. The level indicator is used to ensure that a standard volume of grout is used for each test. The opening at the bottom of the cone is opened and the time for the grout to flow out of the cone is recorded. The test is not considered applicable to grouts that become clogged in the cone and do not continuously flow out the opening. Test results for such mixtures should be discarded.
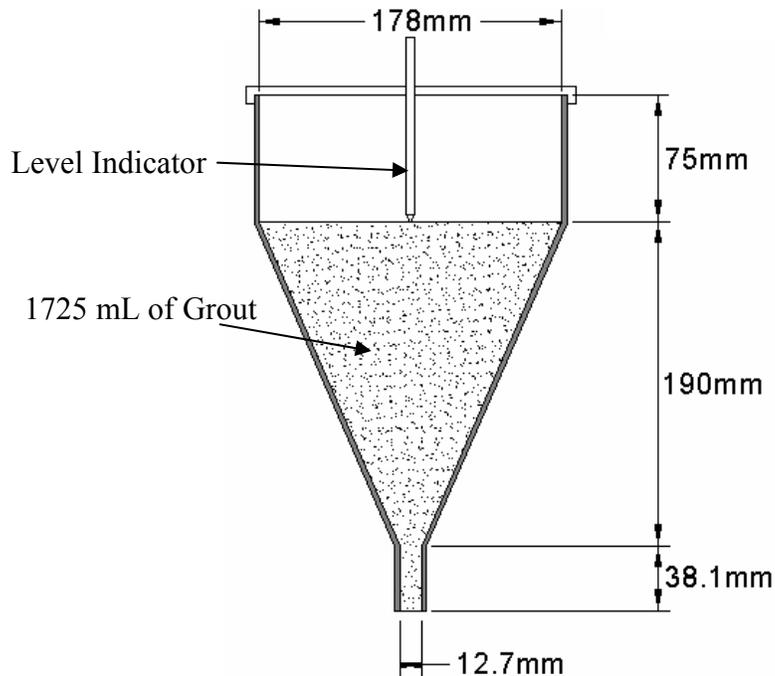
Figure 29: Flow Cone Cross Section

The Marsh cone test (Zhor and Bremner 1998; Ferraris, Obla, and Hill 2001) is a non-standard test most typically used for oil well cements. The Marsh cone is a funnel with a long neck and an opening of 5 mm. A stand holds the Marsh cone in place above a glass graduated cylinder. After one liter of cement paste is placed in the cone, the orifice at the bottom of the neck is opened. The time for various volumes of paste to flow out of the orifice is measured. Since the weight of the cement paste in the funnel should be sufficient to overcome the yield stress, the time of flow should be related to viscosity. However, Ferraris, Obla, and Hill (2001) showed that the flow time from the Marsh cone test was not correlated to the viscosity measured with a laboratory parallel plate rheometer and hypothesized that the lack of correlation was related to factors such as friction and sedimentation in the Marsh cone.

The flow cone test has been adapted for measuring concrete (Ferraris 1999). The larger funnel used for concrete is 615 mm long with a 150 mm long outlet. The upper diameter of 230 mm narrows to 75 mm at the orifice. The device can be used for concretes with aggregate up to 20 mm.

3.3.2 Turning Tube Viscometer

The turning tube viscometer (Hopkins and Cabrera 1985; Ferraris 1999) is based on the same principle as the moving sphere viscometer—namely, Stoke's Law—but is only considered appropriate for testing mortar.

An 800 mm long, 60 mm diameter tube is attached to a rotating arm, which allows the tube to be rotated in the vertical plane. A metal ball is allowed to fall through the fresh mortar in the tube.

A magnet can be placed on the specially milled end caps to ensure that the ball starts in the center of the tube. Inductance coils wrapped around the tube at two locations detect when the ball passes in order to determine the time for the ball to fall a known distance.

The test is conducted with different ball diameters and the results of the test are plotted on a graph of the inverse of the ball diameter squared versus time. The apparent viscosity of the concrete can be calculated based on Stoke's law. Since the assumption in Stoke's law that the ball is moving slowly through a fluid of infinite size is not valid for the test apparatus, correction factors are applied to provide a more accurate result.

The dimensions of the device are not large enough to permit the turning tube viscometer to be used for concrete. The ball diameter should be significantly greater than the maximum aggregate size so that the fluid can be considered a uniform medium. Further, the diameter of the tube should be sufficiently large to avoid interlocking of aggregate particles, which could interfere with the ball's descent.
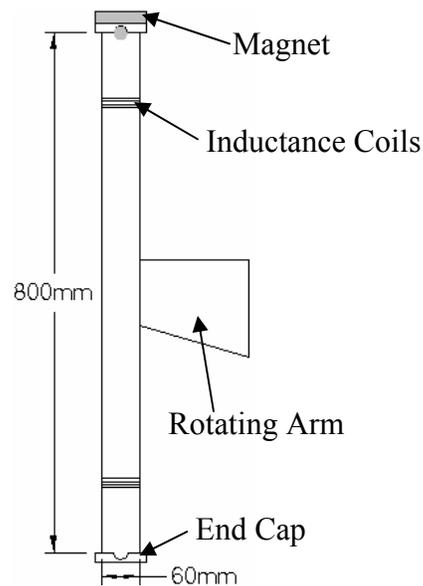
Figure 30: Turning Tube Viscometer

3.3.3   Wuerpel Device

The Wuerpel device (Maultzsch 1990) measures the consistency of mortars by applying a shear force to a mortar specimen and measuring deformation energy.

The apparatus consists of a quadratic mold with side lengths of 100 mm and a height of 50 mm. The corners of the mold are hinged to allow the mold, which is filled with compacted mortar, to deform from a square shape to a rhombus shape. The operation of the device is depicted conceptually in Figure 31. A load cell and a displacement transducer continuously measure the deformation force and the displacement of the mold, respectively. The area under the resulting

force-displacement curve represents the deformation energy, which is used to characterize workability.
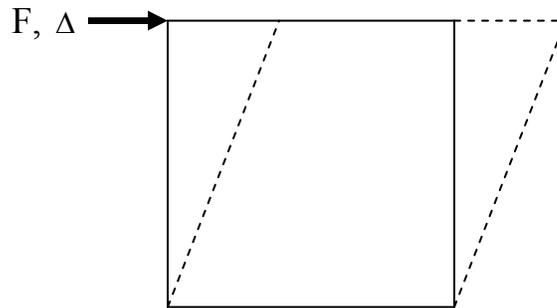
Figure 31: Operation of the Wuerpel Device

The test method was developed in Germany and was briefly included in German standards in the late 1960s. Maultzsch (1990) used the test to measure the change in workability with time for mortars with a maximum aggregate size of 4 mm and found that the test device works particularly well for stiff mortars, although it is applicable to a wide range of concrete workability. The results of the test are dependant on the deformation speed of the device.

3.3.4 Mini-Slump Test

The mini-slump test, which was originally developed by Kantro (1980) and later modified by Zhor and Bremner (1998), measures the consistency of cement paste.

The mini-slump cone is simply a small version of the slump cone. The mini-slump cone has a bottom diameter of 38 mm, a top diameter of 19 mm, and a height of 57 mm. The cone is placed in the center of a square piece of glass on which the diagonals and medians are traced. The cone is lifted and after one minute, the average spread of the paste, as measured along the two diagonals and two medians, is recorded.

Zhor and Bremner (1998) modified the device in order to measure more effectively the air entraining and plasticizing effects of admixtures on cement pastes. A clear plexiglass sheet, which is used instead of glass, is set on a balance. After the cone is removed, the mass of the concrete is measured and used to determine the air content of the paste in accordance with ASTM C185. The paste is left to harden on the plexiglass for two days. A planimeter is then used to measure the area of the hardened paste on the plexiglass sheet.

Like the conventional slump test, the results of the mini-slump test should be related to yield stress. Research conducted by Ferraris, Obla, and Hill (2001) into the influence of mineral admixtures on the rheology of cement paste showed poor correlation between the results of the mini-slump test and yield stress, as measured with a sophisticated, laboratory grade parallel plate rheometer.

3.3.5 Mini-Flow Test

The mini-flow test (Zhor and Bremner 1998) is a variation of the mini-slump test described in the above subsection. The plexiglass sheet used in the modified version of the mini-slump test is mounted to a standard flow table, as described in ASTM C230. After the mini-slump cone is lifted from the sample of cement paste, the table is dropped 15 times in 15 seconds. The rest of the test procedure is unchanged. The mass of the cement paste is measured in order to determine air content. The results of the mini-flow test reflect the addition of energy to the cement paste. The mini-flow test is more appropriate than the mini-slump test for stiff mixes.

3.3.6 Vicat Needle Test

The setting time of concrete, mortar, or paste can be measured as an indication of workability (Ferraris 1999). One of the most common tests is the Vicat needle test for testing cement paste (ASTM C191). The Vicat needle test is also used in ASTM C953 for grout for pre-placed aggregate concrete.

The Vicat needle apparatus consists of a 300 g moveable rod with a 1 mm diameter needle at one end. The rod slides through a frame, where an indicator on the rod moves over a scale mounted to the frame. A specimen of fresh cement paste prepared in a certain proscribed manner is placed in a conical ring below the frame. After thirty minutes the needle is placed on the cement paste specimen and allowed to settle under its own weight. The depth of penetration is recorded from the scale. The test is repeated every 15 minutes (10 minutes for Type III cement) until a penetration depth of less than 25 mm is obtained. Each subsequent reading is taken at a different location on the paste specimen.

Similarly, the penetration test method described in ASTM C403 is used to determine the setting time of concrete by measuring the penetration resistance of mortar specimens sieved from concrete samples. Unlike the Vicat needle test, the apparatus used in ASTM C403 measures the force required to cause penetration, not the depth of penetration.

3.3.7 ViscoCorder

The ViscoCorder is a single-point device used in Germany to measure the consistency of fresh mortar. Banfill (1990) modified the test to measure both the yield stress and plastic viscosity of mortar.

The device consists of a metal cylinder mounted on a rotating turntable. A paddle inserted in the cylinder is connected to a calibrated spring that measures the torque on the paddle. As the cylinder is rotated, the mortar applies a torque to the paddle. Traditionally, the device was operated at only one rotation speed. Banfill (1990) modified the device to measure torque at multiple rotation speeds. To obtain a plot of torque versus speed, the speed of the cylinder is changed in steps from zero to a maximum speed and back to zero. Unlike other rheometers, the device is not automated to change rotation speed and continuously record torque versus time. The device can be calibrated to correlate values for torque and speed to yield stress and plastic viscosity.

Banfill (1990) found that the ViscoCorder works well for fluid mortars; however, stiff mortars slip on the wall of the container, resulting in torque readings that are not an accurate representation of rheology. The container does not include any protrusions to prevent slip.

4   COMMENTS ON EXISTING WORKABILITY TEST METHODS

Numerous conclusions can be drawn from the workability test methods presented in this document by studying what has worked and what has not worked. These conclusions are valuable in developing new workability test methods.

It is perhaps most instructive to study the slump test because of its extensive use over more than 80 years. The slump test has even been used as a simple indication of yield stress in non-concrete applications (Pashias et al. 1996). The lessons drawn from the slump test must not be overlooked in the future development of workability test methods. The slump test has endured longer than any other test method because of its simplicity and the relevance of its results. (Various references cite different dates for the first introduction of the slump test (Chapman 1913; Abrams 1918). The slump test was first standardized into ASTM in 1922.)

Even at the time when the slump test was developed, the test's simplicity was one of its key selling points. No other test is as simple, fast, and reliable as the slump test. However, one of the main disadvantages of the slump test is that it is a static, not dynamic, test. Any new test method should be similar to the slump test in terms of simplicity, speed, and accuracy, while also giving a better indication of the dynamic properties of concrete under actual placing conditions.

Despite criticisms that the results of the slump test can be too easily "adjusted" to meet a specification, the results of the slump test are highly sensitive to changes in material properties. To evaluate the ability of the slump test to detect changes in material properties, Baker and McMahon (1969) compiled the testing, sampling, and material variances for the slump test on eleven construction projects from two states, as shown in Table 7. Testing variance is a measure of testing errors and uncertainties in the test; sampling variance is a measure of errors and uncertainty in the sampling process; and material variance is a measure of changes in material properties. In an ideal test, all of the variance will be attributable to material variance.

The testing variances as a percentage of total variance reported in Table 7 compare favorably to other commonly used test procedures. As reported by Popovics (1994), the pressure method for determining air content (ASTM C233) has a 21.5% testing variance, the 28 day compressive strength test (ASTM C39) exhibits a 16.8% testing variance, and the standard unit weight determination (ASTM C138) has a 51.0% testing variance.

Table 7: Variability in Slump Test Measurements in Highway Applications (Baker and McMahon 1969)

	Project	Observations	Testing Variance	Sampling Variance	Material Variance	Overall Standard Deviation	Mean	Testing Variance as % of Total Variance
State 1	1	184	0.16	0.04	0.26	0.68	2.44	35%
	2	200	0.13	0.02	0.45	0.80	1.50	22%
	3	300	0.25	0.09	0.46	0.89	2.76	31%
State 2	1	216	0.074	0.00	0.15	0.47	2.04	33%
	2	200	0.06	0.06	0.37	0.70	1.86	12%
	3	200	0.08	0.025	0.42	0.73	2.34	15%
	4	200	0.027	0.012	0.206	0.495	1.77	11%
	5	204	0.066	0.03	0.305	0.633	2.37	16%
	6	200	0.033	0.034	0.14	0.456	2.12	16%
	7	200	0.084	0.086	0.20	0.609	2.41	23%
	8	200	0.158	0.047	0.50	0.844	2.26	22%

Aside from the slump test, the remaining workability test methods can be split into two groups: tests that have been used in the concrete industry but not to the extent of the slump test and tests that have never gained acceptance beyond any initial studies. The most notable test methods that have found some use by the concrete industry include the compaction factor test, Vebe consistometer, Kelly ball test, inverted slump cone test, flow table test, K-slump tester, and trowel test. While some other devices do show promise and may be used more extensively in the future, for now they have gained little acceptance by the concrete industry.

Of the just mentioned devices that have found some use in the concrete industry, all are single-point tests with at least one major disadvantage to the slump test. The compaction factor test has been used more extensively in Britain than in the United States, although overall its use has declined. While the compaction factor test is dynamic and does provide more information than the slump test, it is bulky for common site use and the value of its results are not well understood. The Vebe consistometer is used for very low slump concretes; however, it is too large for site use and is not typically used in cases where the slump test can be used. The Kelly ball test has been shown to be at least as accurate as the slump test, yet it has never gained widespread acceptance. The inverted slump cone test shows promise in properly dealing with the thixotropy of fiber-reinforced concrete; however, the device needs to be better developed in order to measure a wider range of concretes and to allow comparison of test results between different individual test apparatuses. The K-slump tester is commercially available and can be used faster than the slump test; however, it is not as accurate as the slump test. The trowel test is useful; however, due to its subjectivity, it will never be specified or used on a widespread basis.

The rotational rheometers described in this document are still primarily in the research domain; none has been extensively marketed to contractors as a field test device. The concepts used by rotational rheometers do show promise for field use. However, with the exception of the BTRHEOM rheometer, all are too bulky for site use. Even the BTRHEOM rheometer, which

requires a computer and includes seals that must be replaced frequently, needs to be made more rugged for field use. All of the devices are far too expensive, even for most laboratory work. If any of the rotational rheometers could be developed in a smaller, more rugged form and on a mass production basis with inexpensive parts, the cost and practicality of such a rotational rheometer could be competitive with the slump test, given the additional information such a test device could provide.

5   CRITERIA FOR NEW WORKABILITY TEST METHODS

Based on the advantages and disadvantages of the existing workability test methods described in this document, criteria for the creation and evaluation of future test methods can be developed. Any new test method should measure workability more fully than the slump test is capable of doing and be competitive with the slump test in terms of cost and speed. The criteria for any new workability test method are described as follows:

- *Parameters Measured:* Any new test method must measure dynamic properties of moderate and low workability concretes and must appropriately measure concretes that exhibit high thixotropy. To accomplish this, the test must add energy to the concrete, such as with vibration. The test should directly or indirectly measure yield stress and plastic viscosity.
- *Ruggedness:* Any new test device must be sufficiently rugged to be used regularly on a jobsite. Depending on the accuracy of the device, it may also be used in the lab for research and mix proportioning.
- *Workability Range:* Any new test method should be able to measure the widest possible range of workability. The wider the range of workability, the more versatile the device will be and the greater the chance that the device will be adopted widely. In reality, no device can measure all concretes, from zero-slump to self-compacting concretes.
- *Aggregate Size Restrictions:* The device must feature proper geometry to allow testing of concretes with a wide range of aggregate sizes. Based on existing tests, such as the slump test, the device should measure concretes with a maximum aggregate size of up to 1.5 inches.
- *Cost:* The cost of any device, when mass-produced, must be competitive with simple, currently available devices, most notably the slump test.
- *Sample Size:* The sample size should be kept to a minimum while still being sufficiently large to accurately determine rheology parameters.
- *Test Speed:* The speed with which the test can be conducted must be minimized. The slump test can be performed in several minutes. Other tests allow workability to be monitored continuously with little interruption of construction operations.
- *Complexity/Training:* Any new test device must be sufficiently simple to be performed and interpreted by field workers. Although the test may report results in terms of yield stress and plastic viscosity, field personnel not familiar with concrete rheology must be able to interpret these values and make quick decisions. The use of nomographs or an embedded electronic device can facilitate the interpretation of results in the field.
- *Data Processing:* The results of the test should preferably be obtained directly without any calculations or processing. When data processing is required, an embedded

electronic device should perform all calculations and display simple results that can be used directly.

- *Size and Weight:* The device must be small and light so that one person can easily move it around on a jobsite.
- *Number of People Required to Perform Test:* One person should be able to perform the test method quickly. This one person should also be able to perform other duties on the job site, instead of only monitoring workability.
- *Electricity:* Although any new test device should preferably be able to operate without electricity, devices requiring power should not be eliminated. Many construction sites have power readily available. Alternatively, batteries can be used.

Most importantly with any device, it must be accepted by a wide range of parties within the concrete industry. As such, the device must satisfy the seemingly conflicting objectives of being simple and rheologically accurate. Concrete contractors will not decide to use a new test unless it clearly adds value to their construction operations. Researchers have been skeptical of simple devices that give a relevant indication of workability but do not directly measure the fundamental rheological properties of concrete. For instance, in discussing the inverted slump cone test for fiber-reinforced concrete, Tattersall and Banfill (1983, 238) write, "it is extremely unfortunate that in a new area of concrete technology it is proposed to establish yet another empirical and quite arbitrary test for workability; the long-term result can only be to add to the confusion which already exists." A device that meets the majority of the criteria enumerated above stands the greatest chance of being adopted by all diverse parties in the concrete industry.

6   CONCLUSIONS

Despite nearly a century of efforts to develop a test method to measure workability quickly and accurately, much work remains to be done. The 61 workability test methods described in this document provide a basis for identifying the principles and concepts that have and have not worked and for developing requirements for a new test method.

Throughout the literature, numerous references quickly rule out the possibility of using a field workability test that does not directly measure yield stress and plastic viscosity. However, no one has proposed a simple, rugged, inexpensive field test to measure the fundamental rheological parameters of concrete. The slump test has endured for nearly 90 years because of its simplicity and accuracy. In fact, some might say that the concrete industry has become complacent in measuring workability due to the simplicity of the slump test. On large construction projects where substantial sums of money are spent on producing and placing concrete, the amount of money spent to measure a property as important as workability is insignificant. Still, in order for the concrete industry to spend more money to monitor workability, a compelling alternative to the slump test in terms of cost and accuracy must be developed.

In reality, it is likely that the workability test devices developed in the future for field use will not directly measure yield stress and plastic viscosity. However, it does appear that the workability of concrete can be monitored in the field by measuring properties only related to yield stress and plastic viscosity. Even a test that does directly measure yield stress and plastic

viscosity may not be useful if contractors do not understand the relevance of the test results. The development of new high-performance concretes will make the need for more accurate field characterization of concrete rheology more important. This need for an improved test method along with new understanding of concrete rheology should propel the development of a new test device that can be accepted by the majority of the concrete industry.

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