ACI 238.1R-08

Report on Measurements of Workability and Rheology of Fresh Concrete

Reported by ACI Committee 238

American Concrete Institute®

First Printing
February 2008

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This report provides a comprehensive view of workability of fresh concrete and a critical review of the tests available to measure workability and rheological performance of fresh concrete. The report discusses the factors affecting the performance of fresh concrete and provides a better understanding of the issues related to the design of workable concrete, from no flow (zero-slump) to flow like a liquid (self-consolidating concrete).

Keywords: rheological measurements; rheology; workability; workability measurements.

CONTENTS

ACI 238.1R-08 was adopted and published February 2008.

CHAPTER 1—INTRODUCTION

Fresh concrete properties are related to the properties of hardened concrete. Poor placement or consolidation leads to honeycombing, which reduces compressive strength and increases permeability, thereby leaving the concrete open to chemical attack. Nevertheless, fresh concrete properties are not always properly measured or predicted. The main measurement of workability, the slump test, is not always applicable; at the same slump value, two concretes may exhibit different workabilities. On the other hand, hundreds of tests were designed over the years to measure the workability of concrete. The question is how to select the proper test for the application at hand and how to interpret the results obtained to predict the performance of the concrete in the field in the fresh state.

To address these questions, it is necessary first to define workability in terms of fundamental physical entities, as described in the science of rheology. Therefore, this report has four main parts:

1. Definitions related to rheology and workability;
2. Critical review of the tests available to measure the workability and rheological performance of fresh concrete;
3. Discussion of the factors affecting the performance of fresh concrete; and
4. Examples that illustrate the application of rheology and material science to predict or improve the performance of fresh concrete in the field.

This report presents issues related to the design of a workable concrete for an application. Workable can mean no flow (zero-slump) or flow like a liquid (self-consolidating concrete [SCC]), depending on the application.

CHAPTER 2—RHEOLOGICAL TERMS RELATED TO CONCRETE

2.1—Notation

c = insignificant constant
g = gravity
h = height of slump cone mold
K = consistency
n = power index representing deviation from Newtonian behavior
s = slump, mm
V = volume of slump cone
α = time-dependent parameter
β = constant
$\dot{\gamma}$ = shear rate
ϕ = concentration of solids
ϕ_m = maximum packing density
η = viscosity of suspension
$[\eta]$ = intrinsic viscosity
η_{pl} = plastic viscosity
η_r = relative viscosity
η_s = viscosity of the matrix
η_∞ = apparent viscosity at very high shear rate
ρ = density, kg/m^3
τ = shear stress, Pa
τ_o = yield stress not Bingham
τ_B = Bingham yield stress

2.2—Definitions

Definitions related to concrete rheology and flow are listed in this section. These definitions were taken from the Cement and Concrete Terminology page of the ACI website (http://www.concrete.org/Technical/CCT/FlashHelp/ACI_Terminology.htm). Several of these definitions were based on Hackley and Ferraris (2001), which presents concrete rheology in the wider context of concentrated particle systems.

Bingham model—

$$\tau = \tau_B + \eta_{pl}\dot{\gamma}$$

$$\dot{\gamma} = 0 \text{ for } \tau < \tau_B$$

where
τ = shear stress;
τ_B = yield stress;
η_{pl} = plastic viscosity; and
$\dot{\gamma}$ = shear rate.

The Bingham model is a two-parameter model used for describing the flow behavior of viscoplastic fluids exhibiting a yield stress.

bleeding—the autogenous flow of mixing water within, or its emergence from, a newly placed mixture caused by the settlement of solid materials within the mass.

consistency—the degree to which a freshly mixed concrete, mortar, grout, or cement paste resists deformation. (See also: **consistency, normal**; **consistency, plastic**; and **consistency, wettest stable**.)

consistency, normal—(1) the consistency exhibited when a mixture is considered acceptable for the purpose at hand; or (2) the consistency of cement paste satisfying appropriate limits defined in a standard test method (for example, ASTM C187).

consistency, plastic—condition of mixture such that deformation would be sustained continuously in any direction without rupture.

consistency, wettest stable—the condition of maximum water content at which cement grout and mortar will adhere to a vertical surface without sloughing.

consistency factor—a measure of grout fluidity, roughly analogous to viscosity, that describes the ease with which grout may be pumped into pores or fissures; usually a laboratory-measured parameter in which consistency is reported in degrees of rotation of a torque viscometer in a specimen of grout.

consolidation—The process of reducing the volume of voids in a mixture, usually accomplished by inputting mechanical energy. (See also **vibration**, **rodding**, and **tamping**.)

finishing—leveling, smoothing, consolidating, and otherwise treating surfaces of fresh or recently placed concrete or mortar to produce desired appearance and service. (See also **float** and **trowel**.)

impending slough—consistency of a shotcrete mixture containing the maximum amount of water such that the product will not flow or sag after placement.

plastic viscosity η_{pl}—(1) for ideal Bingham materials, the difference between the shear stress and the yield stress divided by the shear rate; (2) for non-ideal Bingham materials, the plastic viscosity is determined in the high-shear limiting, linear portion of the flow curve.

segregation—(1) nonuniform concentration of components in mixed concrete or mortar; or (2) nonuniform distribution of size fractions in a mass of aggregate. (See also **bleeding** and **separation**.)

separation—(1) divergence from the mass and differential accumulation of coarse aggregate during movement of the concrete; (2) divergence from the mass and differential accumulation of large coarse aggregate from the bulk coarse aggregate as it is being moved; or (3) the gravitational settlement of solids from a liquid. (See also **bleeding** and **segregation**.)

shear-thinning (pseudoplastic)—a decrease in viscosity with increasing shear rate during steady shear flow.

slump—a measure of consistency of freshly mixed concrete, mortar, or stucco equal to the subsidence measured to the nearest 5 mm (1/4 in.) of the molded specimen after removal of the slump cone.

stability—relative tendency for solid particles suspended in a mixture to maintain uniform distribution. (Note: This is important in SCC.)

stability, dynamic—stability of a mixture during handling, placement, and flow.

stability, static—stability of a mixture that is not flowing.

thixotropy—a reversible, time-dependent decrease in viscosity when a fluid is subjected to increased shear stress or shear rate.

viscoplasticity—the property of a material that behaves like a solid below some critical stress value but flows like a viscous liquid when this stress is exceeded. (See also **yield stress**.)

viscosity—a measure of the resistance of a fluid to deform under shear stress.

workability—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.

yield stress τ_B—a critical shear stress value below which an ideal plastic or viscoplastic material behaves like a solid (that is, will not flow). Once the yield stress is exceeded, a plastic material yields (deforms plastically), while a viscoplastic material flows like a liquid.

2.3—Shear flow curves

Steady shear flow curves for suspensions can exhibit various types of behavior as a function of shear rate. Concrete is known to exhibit either Bingham or the shear-thinning (also called pseudoplastic) behavior. The following classification system covers the six most frequently encountered flow types, as illustrated in Fig. 2.1 and described by Hackley and Ferraris (2001). The numbers in the following list correspond to the curve numbers in Fig. 2.1.

1. **Newtonian**—Differential viscosity and coefficient of viscosity are constant with shear rate;

2. **Shear thickening**—Differential viscosity and coefficient of viscosity increase continuously with shear rate. No yield stress;

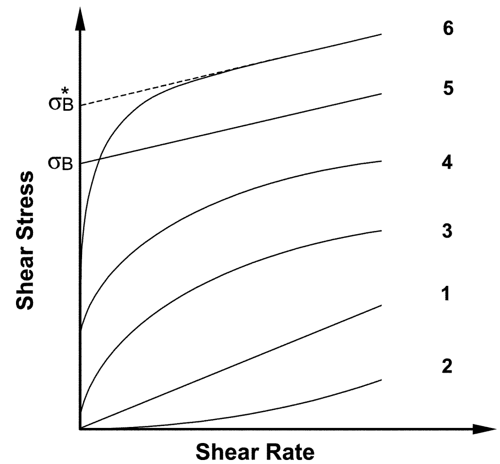

Fig. 2.1—Identification of flow curves based on their characteristic shape.

3. **Shear thinning (pseudoplastic)**—Differential viscosity and coefficient of viscosity decrease continuously with shear rate. No yield stress;

4. **Shear thinning (pseudoplastic) with yield response**—Differential viscosity and coefficient of viscosity decrease continuously with shear rate once the apparent yield stress σ_{app} has been exceeded;

5. **Bingham plastic (ideal)**—Obeys the Bingham relation ideally. Above the Bingham yield stress (σ_B in Fig. 2.1), the differential viscosity is constant and is called the plastic viscosity, while the coefficient of viscosity decreases continuously to some limiting value at infinite shear rate; and

6. **Bingham plastic (non-ideal)**—Above the apparent yield stress, the coefficient of viscosity decreases continuously while the differential viscosity approaches a constant value with increasing shear rate. Extrapolation of the flow curve from the linear, high shear rate region (plastic region) to the stress axis gives the apparent Bingham yield stress (σ_B* in Fig. 2.1). The differential viscosity in the linear region is termed the plastic viscosity.

2.3.1 *Rheological models for materials without yield stress*

- Newton's Law
  $\tau = \eta\dot{\gamma}$

- Power Law
  $\tau = K\dot{\gamma}^n$

2.3.2 *Rheological models for materials with non-zero yield stress* ($\tau_0 \neq 0$)

- Bingham
  $\tau = \tau_B + \eta_{pl}\dot{\gamma}$

- Modified Bingham
  $\tau = \tau_0 + \eta_{pl}\dot{\gamma} + c\dot{\gamma}^2$

- Herschel-Bulkley
  $\tau = \tau_0 + K\dot{\gamma}^n$

- Casson
  $\tau = \tau_0 + \eta_\infty \dot{\gamma} + 2(\sqrt{\tau_0 \eta_\infty})\sqrt{\dot{\gamma}}$

- De Kee
  $\tau = \tau_0 + \eta_{pl}\dot{\gamma}e^{-\alpha\dot{\gamma}}$

- Yahia-Khayat
  $\tau = \tau_0 + 2(\sqrt{\tau_0 \eta_\infty})\sqrt{\dot{\gamma}e^{-\alpha\dot{\gamma}}}$

where

τ_0 = yield stress (Pa);
η_{pl} = plastic viscosity (Pa·s);
$\dot{\gamma}$ = shear rate (s^{-1});
c = insignificant constant;
K = consistency;
n = power index representing the deviation from the Newtonian behavior;
α = time-dependent parameter; and
η_∞ = apparent viscosity at very high shear rate.

2.3.3 *Models predicting rheological properties of suspensions*

- Einstein's model
  $\eta = \eta_s(1 + 2.5\phi)$

- Krieger-Dougherty model

$$\eta_r = \frac{\eta}{\eta_s}\left(1 + \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m}$$

where

η = viscosity of the suspension;
η_s = viscosity of the matrix;
η_r = relative viscosity;
ϕ = concentration of solids;
ϕ_m = maximum packing density; and
$[\eta]$ = intrinsic viscosity defined as

$$[\eta] = \lim_{\phi \to 0}\left(\frac{\eta_r - 1}{\phi}\right)$$

CHAPTER 3—TEST METHODS

3.1—Introduction

Since the early twentieth century, the concrete industry has recognized the need to monitor concrete workability to ensure that concrete can be properly placed and can achieve adequate properties in the hardened state. Numerous test procedures for determining workability have been developed for research, mixture 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, no test has been developed that is sufficiently compelling to convince the concrete industry to replace the slump test.

More advanced concrete production systems have not eliminated the need to monitor concrete workability in the field. To the contrary, the advent of new high-performance concrete mixtures that are susceptible to small changes in mixture proportions has made monitoring workability even more critical. 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 section of the report describes 69 test methods that could be used for measuring concrete workability. While this list is not exhaustive, it includes most of the test methods that have been described in United States and western European literature. Many more tests have been developed for a single project or for a specific application, and have been sparsely reported in the literature, if at all. Despite the fact that many of the devices in this document will never be used 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 evaluation of new test methods.

This section describes key principles and trends in the measurement of workability and then describes the 69 test methods. Based on the successes and failures of past test methods and the current needs of the concrete industry, requirements are presented for evaluating the suitability of new test methods for measuring workability.

3.2—Principles of measurements

The term "workability" is broadly defined; no single test method measures all aspects of workability. ACI Cement and Concrete Terminology (http://www.concrete.org/Technical/CCT/FlashHelp/ACI_Terminology.htm) describes workability as "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished." The Japanese Association of Concrete Engineers defines workability as "that property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed, and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials" (Ferraris 1999). Neville (1996) 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, for example, 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 twentieth century, concrete researchers were just beginning to recognize the importance of water content in predicting concrete strength (Wig 1912; Abrams 1922). The

Table 3.1—Classes of workability measurement (Tattersall 1991)

Class I: qualitative (workability, flowability, compactability, finishability, pumpability)	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)	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)	To be used strictly in conformance with standard definitions

slump test gives an indication of the water content and, thus, the strength of hardened 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. Many of the new methods developed since the establishment of concrete as a Bingham fluid have attempted to measure yield stress non-Bingham 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 3.1. The majority of workability test methods fall into Classes II and III.

Similar to Tattersall's scheme (1991), most test methods for workability have traditionally been split between single-point and multi-point tests. The concept of single-point 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, 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 properties. 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 3.2.

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 mixture or a certain application even though the test does not fully measure fundamental rheological parameters. The tradeoff between single-point and multi-point tests is generally between simplicity and completeness of results.

Table 3.2—Single-point and multi-point workability tests for concrete

Single-point tests	Multi-point tests
1. Angles flow box test	1. Beretta apparatus
2, Compaction factor test	2. BML viscometer
3. Compaction test	3. BTRHEOM rheometer
4. Cone penetration test	4. CEMAGREF-IMG
5. Delivery-chute depth meter	5. Concrete truck mixer as rheometer
6. Delivery-chute torque meter	6. Consolis rheomixer
7. Flow table test (DIN)	7. CONVI viscoprobe
8. Flow trough test	8. FHPCM
9. Free orifice (Orimet) test	9. IBB rheometer
10. Fresh Concrete Tester 101	10. ICAR rheometer
11. Intensive compaction test	11. Modified slump test
12. Inverted slump cone test	12. Multiple single-point tests
13. LCL flow test	13. Powers and Wiler plastometer
14. K-slump tester	14. Rheometer-4SCC
15. Kango hammer test	15. SLump Rate Machine (SLRM)
16. Kelly ball test	16. System and method for controlling concrete production
17. Moving sphere viscometer	17. Tattersall two-point device
18. Powers remolding test	18. Vertical pipe apparatus
19. Proctor test	19. Vibrating slope apparatus
20. Mixer devices	
21. Ring penetration test	
22. Settlement column	
23. Segregation test	
24. Slump test	
25. Soil direct shear test	
26. Soil triaxial test	
27. Surface settlement test	
28. Thaulow tester	
29. Trowel test	
30. Vebe consistometer	
31. Vibratory flow meter	
32. Vibropenetrator	
33. Wigmore consistometer	

Table 3.3—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 applied pressure through a narrow orifice.
Free flow tests	The materials either flows under its own weight, without any confinement, or an object penetrates the material by gravitational settling.
Vibration tests	The materials flows under the influence of applied vibration. The vibration is applied 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 surfaces, one or both of which are rotating.

A distinction can also be made between dynamic 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. Static tests (also referred to as quasi-static tests), however, 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 3.3.

Table 3.4—Categorization of workability test methods*

Tests for concrete (3.3.1)		Tests for self-consolidating concrete (3.3.2)	Tests for pastes and grouts (3.3.3)
>*Confined flow tests* (3.3.1.1) —Compaction factor test (3.3.1.1.1) —Free orifice test (Orimet test) (3.3.1.1.2) —K-slump tester (3.3.1.1.3) >*Free flow tests* (3.3.1.2) —Cone penetration test (3.3.1.2.1) —Delivery-chute depth meter (3.3.1.2.2) —Delivery-chute torque meter (3.3.1.2.3) —Flow trough test (3.3.1.2.4) —Kelly ball test (3.3.1.2.5) —Modified slump test (3.3.1.2.6) —Moving sphere viscometer (3.3.1.2.7) —Ring penetration test (3.3.1.2.8) —SLump Rate Machine (SLRM) (3.3.1.2.9) —Slump test (3.3.1.2.10) —Surface settlement test (3.3.1.2.11) >*Vibration tests* (3.3.1.3) —Angles flow box test (3.3.1.3.1) —Compaction test (3.3.1.3.2) —Flow table test (DIN flow table) (3.3.1.3.3) —Inverted slump cone test (3.3.1.3.4) —LCL flow test (3.3.1.3.5) —Powers remolding test (3.3.1.3.6) —Settlement column segregation test (3.3.1.3.7) —Thaulow tester (3.3.1.3.8) —Vebe consistometer (3.3.1.3.9) —Vertical pipe apparatus (3.3.1.3.10) —Vibrating slope apparatus (3.3.1.3.11) —Vibratory flow meter (3.3.1.3.12) —Vibropenetrator (3.3.1.3.13) —Wigmore consistometer (3.3.1.3.14)	>*Rotational rheometers* (3.3.1.4) —Bertta apparatus (3.3.1.4.1) —BML viscometer (3.3.1.4.2) —BTRHEOM rheometer (3.3.1.4.3) —CEMAGREF-IMG (3.3.1.4.4) —Concrete truck mixer as rheometer (3.3.1.4.5) —Consolis Rheomixer® (3.3.1.4.6) —CONVI Visco-Probe (3.3.1.4.7) —FHPCM (3.3.1.4.8) —Fresh concrete tester 101 (FCT 101) (3.3.1.4.9) —ICAR rheometer (3.3.1.4.10) —IBB rheometer (3.3.1.4.11) —Mixer devices (3.3.1.4.12) —Powers and Wiler plastometer (3.3.1.4.13) —Rheometer-4SCC (3.3.1.4.14) —Soil direct shear test (3.3.1.4.15) —Tattersall two-point device (3.3.1.4.16) >*Tests for very high yield-stress concrete* (3.3.1.5) —Intensive compaction test (3.3.1.5.1) —Kango hammer test (3.3.1.5.2) —Proctor test (3.3.1.5.3) >*Other test methods* (3.3.1.6) —Multiple single-point tests (3.3.1.6.1) —Soil triaxial test (3.3.1.6.2) —System and method for controlling concrete production (3.3.1.6.3) —Trowel test (3.3.1.6.4)	>*Confined flow tests* —Fill box test (3.3.2.2) —L-box test (3.3.2.4) —Simulated soffit test (3.3.2.6) —U-box test (3.3.2.8) —V-funnel test (3.3.2.9) >*Free flow tests* —J-ring test (3.3.2.3) —Slump flow test (3.3.2.7) >*Stability tests* —Column segregation test (3.3.2.1) —Penetration test for Segregation (3.3.2.5) —Wet sieving stability test (3.3.2.10)	—Flow cone and marsh cone tests (3.3.3.1) —Lombardi plate (3.3.3.2) —Mini-flow test (3.3.3.3) —Mini-slump test (3.3.3.4) —Rotational rheometers —Turning tube viscometer (3.3.3.5) —Vicat needle test (3.3.3.6) —ViscoCorder (3.3.3.7) —Wuerpel device (3.3.3.8)

*Tests placed in alphabetical order.

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 should be recognized that some existing test methods, such as many of the tests for high yield-stress concrete, do not directly measure the flow properties of concrete and therefore do not fit into any of the four categories in Table 3.3. The results of these tests, however, can still give meaningful information on concrete workability.

3.3—Description of existing test methods

The 69 workability test methods described in this document are presented in accordance with the NIST flow-type classification scheme. Because concrete, paste and grout, and SCC are each rheologically unique, test methods for each material can be divided into separate categories, as shown in Table 3.4. Some test methods that do not fit into any of the four NIST flow-type categories are described in separate categories.

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

3.3.1 *Workability tests for concrete*—The workability test methods for concrete presented in this document cover a broad range, from extremely dry, roller-compacted concrete to SCC. 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. Many of the test methods measure the flowability of concrete; however, only a few test methods are currently available for measuring the homogeneity of concrete. Tests for homogeneity are generally applied to concretes with high flowability, such as SCC, where segregation often is a problem. 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.

3.3.1.1 *Confined flow tests*—Only three confined flow test methods for concrete are presented in this document. The use of confined flow in measuring workability, however, is much more extensive than this short list suggests. Many of the tests available for SCC are confined flow tests. Confined flow tests are generally not suitable for high to moderate yield-stress concretes, which are not sufficiently fluid to readily flow under confined conditions and produce meaningful test results. Because vibration imparts energy into concrete and produces flow in high to moderate yield-stress 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.