

Report on Measurements of Workability and Rheology of Fresh Concrete

Reported by ACI Committee 238



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Report on Measurements of Workability and Rheology of Fresh Concrete

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Report on Measurements of Workability and Rheology of Fresh Concrete

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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.

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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;

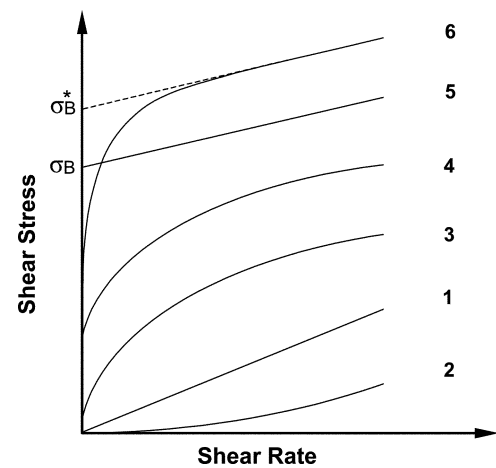


Fig. 2.1—Identification of flow curves based on their characteristic shape.

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

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

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

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

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 (Wicks 1922, Abrams 1922). The

Table 3.1—Classes of workability measurement (Tattersall 1991)

<i>Class I: qualitative</i> (workability, flowability, compactability, finishability, pumpability)	To be used only in a general descriptive way without any attempt to quantify
<i>Class II: quantitative empirical</i> (slump, compacting factor, Vebe time, flow table spread)	To be used as a simple quantitative statement of behavior in a particular set of circumstances
<i>Class III: quantitative fundamental</i> (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)
><u>Confined flow tests</u> (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) ><u>Free flow tests</u> (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) ><u>Vibration tests</u> (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)	><u>Rotational rheometers</u> (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) ><u>Tests for very high yield-stress concrete</u> (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) ><u>Other test methods</u> (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)	><u>Confined flow tests</u> —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) ><u>Free flow tests</u> —J-ring test (3.3.2.3) —Slump flow test (3.3.2.7) ><u>Stability tests</u> —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.

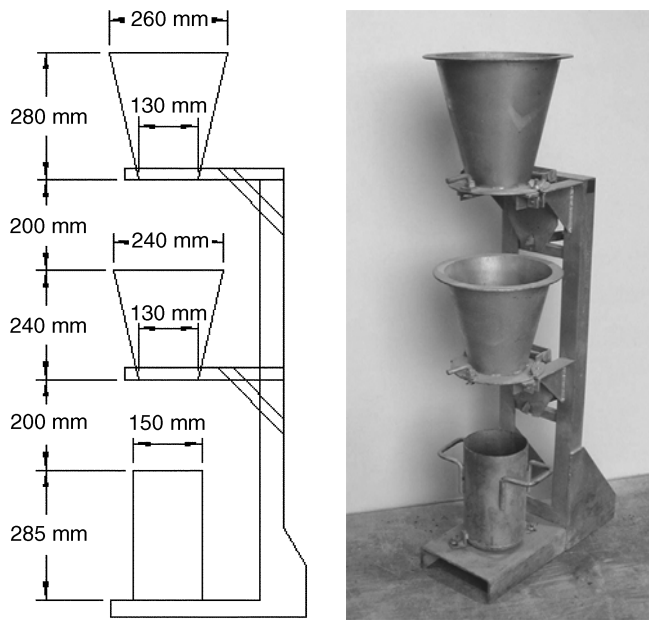


Fig. 3.1—Standard version of compaction factor test apparatus (1 mm = 0.039 in.).

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

3.3.1.1.1 Compaction factor test (or consolidating factor test)—The compaction factor test (Powers 1968; Neville 1996; Bartos 1992; Bartos et al. 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 was standardized as BS 1881-103 (British Standards Institute 1993).

The commercially available apparatus consists of a rigid frame that supports two conical hoppers vertically aligned above each other and mounted above a cylinder, as shown in Fig. 3.1. 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 is 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 with 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 previously described standard test apparatus is appropriate for concretes with aggregate sizes of up to 20 mm

Table 3.5—Interpretation of compaction factor test results as described in British Road Note 4 (Wilby 1991)

Degree of workability	Slump, mm (in.)	Compaction factor		Applications
		Small apparatus	Large apparatus	
Very low	0 to 25 (0 to 1)	0.78	0.80	Vibrated concrete in roads or other large sections.
Low	25 to 50 (1 to 2)	0.85	0.87	Mass concrete foundations without vibration. Simple reinforced sections with vibration.
Medium	50 to 100 (2 to 4)	0.92	0.935	Normal reinforced work without vibration and heavily reinforced sections with vibration.
High	100 to 180 (4 to 7)	0.95	0.96	Sections with congested reinforcement. Not normally suited for vibration

(3/4 in.). A larger apparatus is available for concretes with maximum aggregate sizes of up to 40 mm (1-1/2 in.).

The results of the compaction factor test can be correlated to slump, although the relationship is not linear. Wilby (1991) relates the results of the compaction factor test to slump and a general description of workability (Table 3.5).

The compaction factor test has been used more widely in Europe than in the United States, although the overall use of the test is declining. The test has typically been used in precast operations and at large construction sites. Compared with 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 be reflective of field conditions. Further, the compaction factor test does not use vibration, which is 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; and
- 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 be reflective of field conditions;
- The test method does not use vibration, the main compaction method used in the field; and
- Although the test is commercially available, it is used infrequently.

3.3.1.1.2 Free orifice test (Orimet test)—The free orifice test (Bartos 1992; Bartos 1994; Wong et al. 2000;

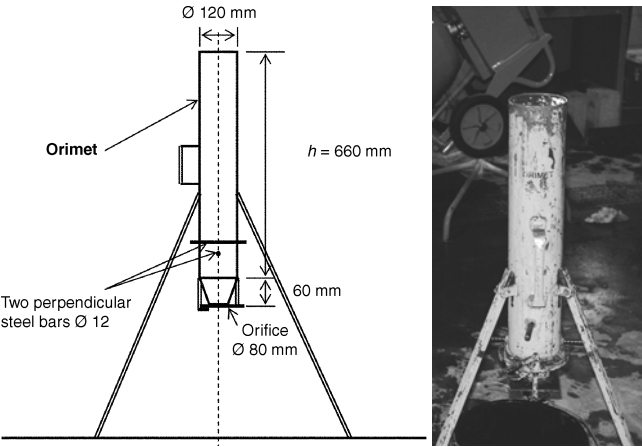


Fig. 3.2—Modified Orimet for SCC (with two perpendicular bars) (1 mm = 0.039 in.).

Sonebi and Bartos 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 (23.6 in.) long, 100 mm (3.9 in.) 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 (3.1 in.) is appropriate for concrete mixtures with a maximum aggregate size of 20 mm (3/4 in.). Other typical orifice sizes are 70 and 90 mm (2.8 and 3.5 in.). To perform the test, concrete is placed in the pipe, but is 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 mixtures, Bartos (1992) reported typical flow times of 1.5 to 6 seconds; however, less flowable concretes can have flow times longer than 60 seconds. If a mixture is highly susceptible to segregation, coarse aggregates tend to accumulate near the orifice and slow or completely block flow. A noncontinuous discharge can suggest a concrete mixture’s susceptibility to segregation. The standard test requires approximately 7.5 L (0.26 ft³) of concrete, and should be repeated at least two or three 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 the apparatus is easily portable; however, it requires modifications to measure a wider range of concrete mixtures. For concretes with low slump, a vibrator could be attached externally to the pipe to promote flow. Different size aggregates require different size orifices, which 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.

The interparticle friction between the various solids (coarse aggregate, sand, and powder materials) affects filling ability. Such solid-to-solid friction increases the internal resistance to flow, thus limiting the filling ability and speed

Table 3.6—Precision of Orimet flow time (with 70 mm [2.8 in.] orifice)

Orimet flow time, seconds	3	5	8	12	>15
Repeatability <i>r</i> , seconds	0.7	1.6	2.9	4.6	6.6
Reproducibility <i>R</i> , seconds	1.1	2.1	3.5	5.4	6.8

of flow of the fresh concrete. For SCC mixtures, a modified Orimet with 80 mm (3.1 in.) orifice was used in the Brite-Euram Project (1996-2000). In addition, this modified Orimet, which is pictured in Fig. 3.2, included 12 mm (1/2 in.) horizontal steel bars set at right angles to each other to limit the passage of concrete through the orifice and check the blockage (Sonebi and Bartos 2002). Using the old Orimet with an orifice of 80 mm (3.1 in.) and without any bars, the flow time was less than 1 second, which was difficult to measure. For SCC mixtures with a slump flow of 655 mm (26 in.) and a flow time with the modified Orimet of 2.3 seconds, the coefficient of variation and the relative error at 95% confidence limit were 8.3 and 9.6%, respectively (Sonebi and Bartos 2002).

Wong et al. (2000) made several recommendations for modifying the free orifice device to obtain additional information about the concrete mixtures. The time for the concrete to flow out of the tube could be used in addition to slump to better characterize workability. Alternatively, multiple shear rates could be achieved by placing surcharge weights on the concrete. While the idea of using multiple shear rates has been suggested, it is not known if this idea has been attempted.

In a test of antiwashout 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 spread/flow test was performed on the same concrete mixtures, the associated changes in workability due to changes in fine aggregate content were not detected.

Based on interlaboratory testing of SCC with two replicates and 20 operators from 10 laboratories from the European project, Testing SCC (2005), the repeatability *r* and the reproducibility *R* according ISO 5725 for different values of Orimet flow time with an orifice of 70 mm (2.8 in.) are given in Table 3.6.

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; and
- The test represents a good simulation of actual placing conditions for highly flowable concretes.

Disadvantages:

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

3.3.1.1.3 *K-slump tester*—The *K-slump tester* (Nasser and Rezk 1972; Nasser 1976; Nasser and Al-Manaseer 1988;

Bartos 1992; Scanlon 1994; Ferraris 1999; Wong et al. 2000; U.S. Patent and Trademark Office 1975) is a small device that can be inserted directly into a mass of fresh concrete to quickly determine slump. The test was developed by 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 Fig. 3.3. The end with the pointed tip is inserted into the concrete. A flat plate at approximately midheight 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 the workability and compactability of the mixture. The difference between *K* and *W* is an indication of the susceptibility of a mixture to segregation.

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 (U.S. Patent and Trademark Office 1995). The device is appropriate for medium and low yield-stress 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. Because aggregates greater in size than the 9 mm (3/8 in.) 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 1 minute;
- The test can be performed on in-place concrete; and
- 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; and
- The test is static, and is not appropriate for low-slump concrete mixtures.

3.3.1.2 Free flow tests—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 also measure plastic viscosity. Although many of the free flow tests can be used on concretes with a wide range of workability, none of the free flow tests



Fig. 3.3—*K*-slump tester (U.S. Patent and Trademark Office 1975).

features vibration. Tests that do not include vibration may not be the most appropriate test methods for characterizing high yield stress and highly thixotropic concrete mixtures.

3.3.1.2.1 Cone penetration test—The cone penetration test (Sachan and Kameswara Rao 1988) 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 (8.8 lb) 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 to determine the optimum device characteristics. By varying the weight and apex angle, the test developers were able to determine a relationship between the cone weight, cone geometry, the penetration depth, and the properties of the concrete, as shown in Eq. (3-1)

$$d = \frac{KW^n}{\theta} \quad (3-1)$$

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

Sachan and Kameswara Rao (1988) 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 mixtures.

Unlike the inverted slump cone test and Vebe consistometer, the cone penetration test is not dynamic and, therefore, is affected by thixotropy. Because 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; and
- The test can be performed on in-place concrete.

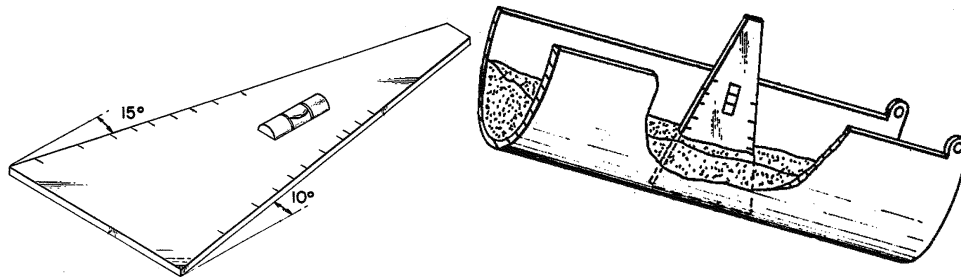


Fig. 3.4—Delivery-chute depth meter (U.S. Patent and Trademark Office 1986).

Disadvantages:

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

3.3.1.2.2 Delivery-chute depth meter—The delivery-chute depth meter (U.S. Patent and Trademark Office 1986; 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 Fig. 3.4. 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 should be calibrated for each concrete mixture tested. For a given concrete mixture, the water content is systematically altered. For each water content, the slump and the depth of flow in the delivery chute are recorded to develop points on the device. Given that each separate concrete mixture needs to be calibrated separately, the device is best suited for jobs where a large quantity of one concrete mixture is being placed.

Advantages:

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

Disadvantages:

- The device needs to be calibrated for each concrete mixture; and
- Any variations in concrete height along the length of the delivery chute could distort readings.

3.3.1.2.3 Delivery-chute torque meter—The delivery-chute torque meter (U.S. Patent and Trademark Office 1982a; 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, shown in Fig. 3.5, is inserted in flowing concrete in the delivery chute of a concrete mixing truck. The two curved sensing blades are attached to a

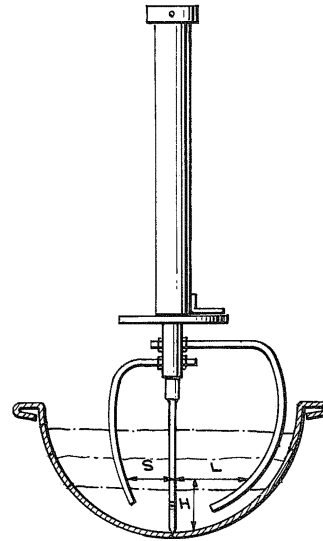


Fig. 3.5—Delivery-chute torque meter (U.S. Patent and Trademark Office 1982a).

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. Because 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 need to be obtained. The geometry of the device allows the device to adjust automatically to changes in flow velocity and height.

Advantages:

- The device measures the workability of the concrete as it exits the mixer before it is placed; and
- The torque (and associated slump) is read directly from the device. No computer or other sensing device is 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; and
- The device must be calibrated for each concrete mixture.

3.3.1.2.4 Flow trough test—The flow trough test (Bartos et al. 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 (9 in.) wide, 1000 mm (39 in.) long horizontal steel trough. Approximately 6 L (0.2 ft³) 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 (29.5 in), down the trough is recorded. The test is conducted three times immediately after mixing and another three times 30 minutes after mixing. The set of tests is conducted at 30 minutes to characterize the workability of the concrete at the time of placement. The concrete is agitated every 5 minutes in the 30 minutes between the initial and final sets of tests. In addition to flow, assessments of bleeding and segregation are made based on a visual examination.

Advantages:

- The test method is simple and inexpensive; and
- 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; and
- The test is not standardized and not widely used.

3.3.1.2.5 Kelly ball test—The Kelly ball test (Powers 1968; Bartos 1992; Scanlon 1994; Ferraris 1999; Bartos et al. 2002) was developed in the 1950s in the United States as an 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 150 mm (6 in.) diameter, 13.6 kg (30 lb) ball attached to a stem, as shown in Fig. 3.6. The stem, which is graduated in 6 mm (0.25 in.) increments, slides through a frame that rests on the fresh concrete. To perform the test, the concrete to be tested is struck off to be level. The ball is released and the depth of penetration is measured to the nearest 6 mm (0.25 in.). At least three measurements need to be made for each sample.

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; the standard was discontinued in 1999 due to lack of

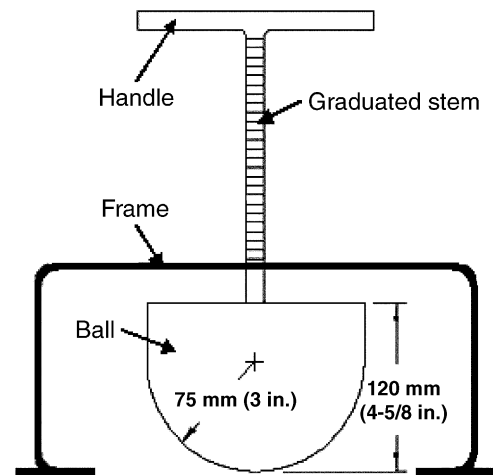


Fig. 3.6—Kelly ball test apparatus.

use. The test has never been used widely outside of 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 mixtures such as lightweight and heavyweight concretes. The precision of the test declines with the increasing size of coarse aggregate (Bartos 1992). The reliability of the results also depends on the maintenance of the apparatus.

Advantages:

- The test is faster than the slump test and can be performed on in-place concrete to obtain a direct result quickly; and
- 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 not widely used; and
- Large aggregate can influence the results.

3.3.1.2.6 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 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/C143M, 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 (4 in.) 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 Fig. 3.7.

The rheological parameters of yield stress and plastic viscosity can be expressed in fundamental units using equations

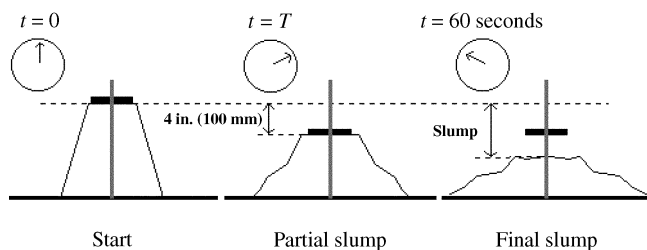


Fig. 3.7—Schematic of modified slump test (Ferraris and de Larrard 1998).

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/m³), as shown in Eq. (3-2). The equation for yield stress is based on experimental measurement with the BTRHEOM rheometer

$$\tau_0 = \frac{\rho}{347}(300 - s) + 212 \quad (3-2)$$

Plastic viscosity (μ , Pa.s) is expressed as a function of final slump, slump time (T , s), and concrete density, as shown in Eq. (3-3). The equation for plastic viscosity is based on a semi-empirical model developed using the results of the modified slump test and the BTRHEOM rheometer

$$\text{For } 200 \text{ mm} < s < 260 \text{ mm: } \eta_{pl} = \rho T \times 1.08 \times 10^{-3}(s - 175) \quad (3-3)$$

$$\text{For } s < 200 \text{ mm: } \eta_{pl} = 25 \times 10^{-3} \rho T$$

Nomographs have been developed based on the aforementioned 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 (4 in.) to be achieved, the test only applies to concrete with slumps ranging from 120 to 260 mm (4.75 to 10.25 in.). 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 (4 in.) below the top of the slump cone (Ferraris 1999). Due to the potentially short time for the disk to descend 100 mm (4 in.), there is a possibility of operator error in determining the precise instances to start and stop the measurement of the slump time. Therefore, the time for the disk to descend 100 mm (4 in.) should be at least 2 to 3 seconds for adequate reproducibility. The SLump Rate Machine (SLRM) described in Section 3.3.1.2.9 automates this measurement, thereby reducing this source of error.

Additional experimental testing needs to be carried out on a wider range of concrete mixtures 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; and

- 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;
- The results of the test could be compromised by operator error in starting and stopping the timer, especially for times less than 2 to 3 seconds; and
- Further testing is required to verify the validity of the test.

3.3.1.2.7 Moving sphere viscometer—The moving sphere viscometer (Powers 1968; Wong et al. 2000) uses the principle of Stokes' 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 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 Stokes' law, the viscosity of the concrete is then calculated as a function of the velocity of the sphere and the force required to move the sphere. Correction factors should be applied to account for assumptions made with regard to Stokes' 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; and
- 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 needs to be quite large 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 need to be measured and used in an equation to calculate viscosity. Additionally, correction factors need to be applied;
- While the test does provide a measure of plastic viscosity, it does not provide a direct measure of yield stress; and
- 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.

3.3.1.2.8 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. Additional weights can be gradually added to the ring until the ring begins to settle into the concrete. The total weight of the ring and of any additional applied weight when the ring begins to penetrate the concrete is related to the yield stress. The rate at which the ring settles when a constant weight is applied can also be measured. The method is considered appropriate for grouts and low yield-stress concretes.

Advantages:

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

Disadvantages:

- The test is only considered appropriate for grouts, mortars, 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; and
- The test is not widely used, and the interpretation of the test results is not well known.

3.3.1.2.9 SLump Rate Machine (SLRM)—Like the modified slump test, the SLump Rate Machine (SLRM) introduces the variable of time to the standard slump test 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 τ_y is a function of concrete density ρ and the horizontal slump flow of the concrete Sf , as shown in Eq. (3-4)

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

where g = gravity, V = volume of the slump cone, and β_1 = constant.

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 Eq. (3-5)

$$\eta = \frac{gHV\rho}{150\pi(Sl)(Sf)^2 t_{slump}} = \beta_2 \frac{\rho}{(Sl)(Sf)^2 t_{slump}} = \quad (3-5)$$

$$\frac{\beta_2}{\beta_1} \frac{\tau_y}{(Sl)} t_{slump}$$

where H = height of slump cone mold, and β_1 = constant.

Based on the previous 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/C143M. A plate rests on top of the concrete cone, and is

attached to a displacement transducer to record slump versus time. The device should 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. The second generation of SLRM (SLRM II) provides two new features: 1) an automatic hydraulic slump cone lifter that removes the slump cone vertically upward at a predetermined rate; and 2) four infrared sensors that are used to monitor the withdrawal rate of the cone, the slump, and spread of the concrete (Chidiac and Habibbeigi 2005; Habibbeigi 2003).

Tests were conducted on multiple concrete mixtures with a wide range of workability to judge the validity of the test device. Equation (3-4) for yield stress and Eq. (3-5) 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; and
- The test is simpler and less expensive than traditional rheometers; however, it provides 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; and
- The test device is more complicated than the modified slump test, and requires the use of a computer to log data and perform calculations.

3.3.1.2.10 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 rapidly determine whether a concrete batch should be accepted or rejected. The test method is widely standardized throughout the world, including in ASTM C143/C143M in the United States and EN12350-2 in Europe (European Committee for Standardization 2000a).

The apparatus, as described in ASTM C143/C143M and EN12350-2, consists of a mold in the shape of a frustum of a cone with a base diameter of 200 mm (8 in.), a top diameter of 100 mm (4 in.), and a height of 300 mm (12 in.). 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 Fig. 3.8. The only type of slump permissible under ASTM C143/C143M 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/C143M advises caution in interpreting test results less than 15 mm (1/2 in.) and greater than 230 mm (9 in.). If part of the concrete shears from the mass, the test should be repeated with a different sample of concrete. A concrete that exhibits

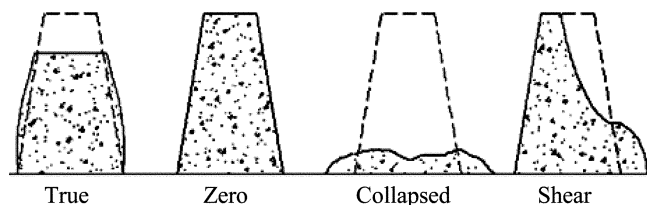


Fig. 3.8—Four types of slump (not to scale).

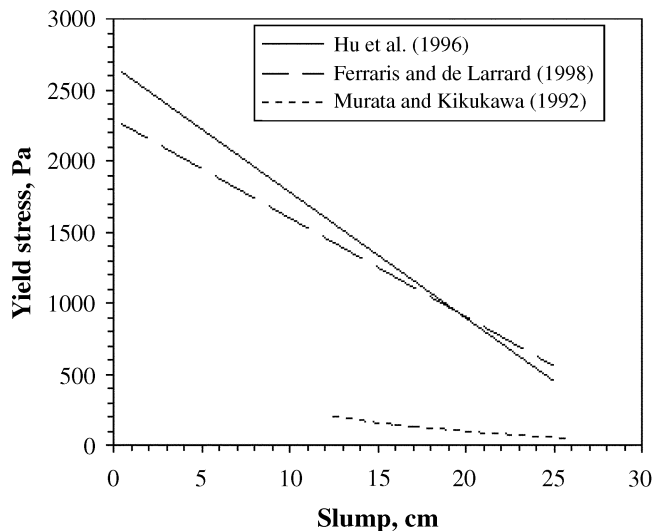


Fig. 3.9—Comparison of equations relating yield stress and slump (1 cm = 0.39 in.; 1000 Pa = 0.145 psi).

a shear slump in a second test is not sufficiently cohesive, and should be rejected.

The slump test is not considered applicable for concretes with a maximum coarse aggregate size greater than 40 mm (1.5 in.). For concrete with aggregate greater than 40 mm (1.5 in.) 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, although such an assessment is not standardized. 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. Because different rheometers measure different absolute values for the yield stress of identical samples of concrete, the experimental equations largely depend 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 Eq. (3-6). The finite element calculations were performed for concretes with slumps

ranging from 0 to 250 mm (0 to 10 in.). 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 Eq. (3-6) and yield stress measurements from the BTRHEOM rheometer. It should be noted that the finite element calculations were performed for concretes with slumps as low as zero, while the BTRHEOM rheometer can only measure concretes with slumps greater than approximately 100 mm (4 in.).

$$\tau_0 = \frac{\rho}{270}(300 - s) \quad (3-6)$$

where τ_0 = yield stress in Pa, s = slump in mm, and ρ = density in kg/m³.

Based on additional experimental measurements with the BTRHEOM, Ferraris and de Larrard (1998) altered Eq. (3-6), as shown previously in Eq. (3-2).

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 125 to 260 mm (5 to 10 in.), as shown in Eq. (3-7)

$$\tau_0 = 714 - 473 \log(s) \quad (3-7)$$

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 Larrard (1998), and Murata and Kikukawa (1992) is presented in Fig. 3.9.

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 10 to 260 mm (0.4 to 10.25 in.). 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) and Domone et al. (1999) have presented experimental data showing a relationship between slump and yield stress. Sobolev (2004) developed a model relating concrete slump to shear stress and volume of the cement paste.

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; and
- Compared with 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 with newer, advanced concrete mixtures than with more conventional mixtures; and
- The slump test cannot distinguish clearly between low-slump mixtures.

3.3.1.2.11 Surface settlement test—The surface settlement test (Khayat 1999) 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 concretes and SCCs; however, it can be used for moderate yield-stress concrete mixtures.

The test apparatus, shown in Fig. 3.10, consists of an 800 mm (31.5 in.) tall, 200 mm (8 in.) 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 (27.5 in.) in the cylinder. Highly fluid concretes and SCCs do not need to be consolidated; however, rodding or vibration is necessary for less-fluid concretes. A 4 mm (0.16 in.) thick, 150 mm (5.9 in.) diameter acrylic plate is placed on the top surface of the concrete. Four 75 mm (3 in.) 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. The determination of the rate of surface settlement after 30 minutes can be used to determine the static stability of the concrete. This value has been closely correlated with the maximum surface settlement value; for example, a rate of settlement of 0.16% per hour would correspond to a maximum settlement of 0.5% (Hwang et al. 2006).

Advantages:

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

Disadvantages:

- The test does not give a direct result; and
- 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,

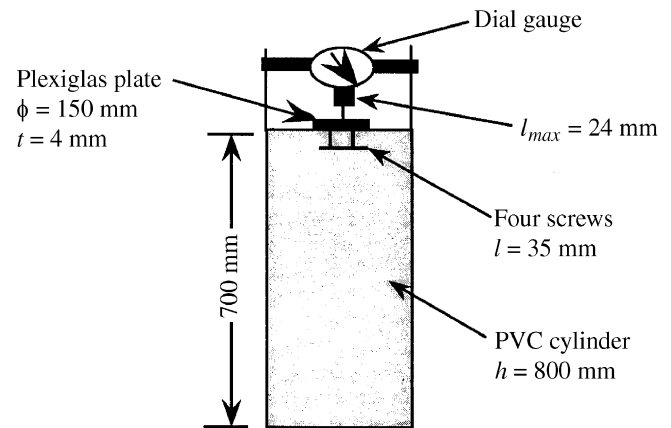


Fig. 3.10—Surface settlement (Khayat 1999) (1 mm = 0.039 in.).

unless the rate of surface settlement after 30 minutes is employed to determine the static stability of the concrete.

3.3.1.3 Vibration tests—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 high and moderate yield-stress concretes that are commonly vibrated in the field. Additionally, 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 was experimentally established (Tattersall and Baker 1989; Banfill et al. 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 et al. (1999) showed 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. Because 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.

3.3.1.3.1 Angles flow box test—The Angles flow box test (Scanlon 1994; Wong et al. 2000) attempts to simulate typical concrete construction 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

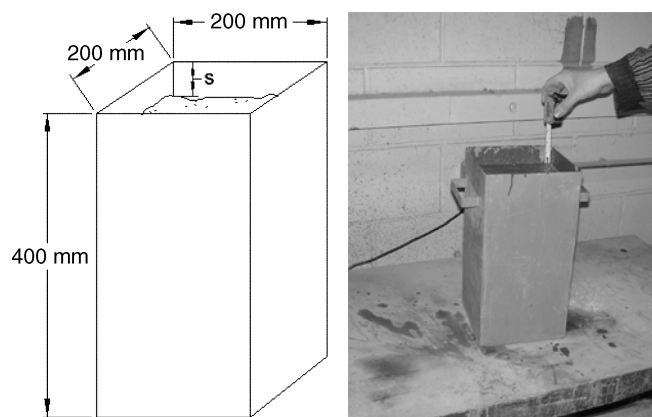


Fig. 3.11—Compaction test apparatus (1 mm = 0.039 in.).

aggregate. The second partition is a solid, removable plate that initially holds concrete on one side of the box before 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 visually observed.

Very little data are 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 mixtures. For highly flowable concrete mixtures, vibration may be unnecessary. A similar concept is used to test the workability of SCC.

Advantages:

- The test method represents actual field conditions. It is a dynamic test that subjects concrete to vibration; and
- 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; and
- The test result is likely a function of both yield stress and plastic viscosity, although these values are not directly recorded.

3.3.1.3.2 Compaction test (Walz test, compaction index test, degree of compaction test)—Like the compaction factor test, the compaction test (Walz 1964; Bartos 1992; Bartos et al. 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 EN12350-4 (European Committee for Standardization 2000c).

The test apparatus, shown in Fig. 3.11, is simple—it consists merely of a tall rigid metal container with side dimensions of 200 mm (7.9 in.) and a height of 400 mm (15.7 in.). 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 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.

A similar test, the Fritsch test (Ferraris 1999), measures not just the distance that the concrete compacts, but also the time it takes for the 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; and
- 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 high yield-stress concretes are tested; and
- 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.

3.3.1.3.3 Flow table test (DIN flow table)—The flow table test (Tattersall 1991; Bartos 1992; Wong et al. 2000; Bartos et al. 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 increased use of highly fluid concretes. The test is sometimes referred to as the DIN flow table, in reference to its inclusion in German specification DIN 1048 (Deutsches Institut für Normung 1991). The test is currently standardized in the European Standards as EN12350-5 (European Committee for Standardization 2000d).

The apparatus consists of a 700 mm (27.6 in.) square wooded top plate lined with a thin metal sheet, as shown in Fig. 3.12. 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 (1.6 in.). Etched into the metal sheet are two perpendicular lines that cross in the center of the plate and a 200 mm (7.9 in.) 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 (5.1 in.), and with a bottom diameter and height of 200 mm (7.9 in.).

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 (1.6 in.) 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 mixtures that are susceptible to segregation, the paste will tend to 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 mixtures 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, before jolting, correlates better to slump (Juvas 1994). Despite its simplicity, the test apparatus is large and needs to 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; and
- The test is very low in cost.

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 not reflect the bulk properties of the concrete; and
- The results are not given in terms of fundamental units. An analytical treatment of the test would be difficult.

3.3.1.3.4 Inverted slump cone test—The inverted slump cone test (Tattersall and Banfill 1983; McWhannell 1994; Johnston 1994; ASTM C995) 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 mixtures incorporating polypropylene fibers show a slight decrease in slump but an increase in workability as measured with the compacting factor test.

The test apparatus comprises readily available job-site equipment: an internal vibrator, slump cone, and bucket. The test is standardized in ASTM C995. A specially constructed wood frame, shown in Fig. 3.13, holds the slump cone in an inverted position above the standard bucket described in ASTM C29/C29M for determination of unit weight. A 100 mm (4 in.) 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,

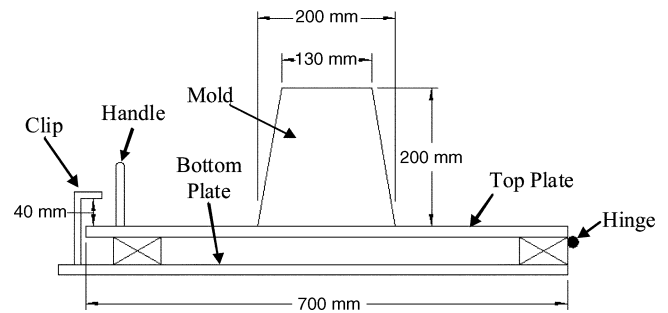


Fig. 3.12—Flow table test apparatus (1 mm = 0.039 in.).

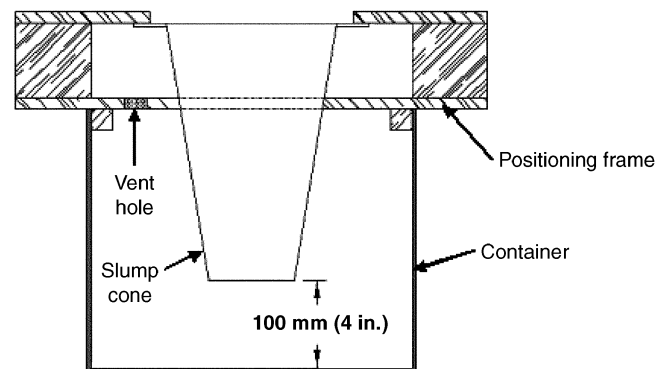


Fig. 3.13—Inverted slump cone test apparatus.

a 25 mm (1 in.) 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 ± 1 second. 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.

ACI 544.2R recommends the use of the inverted slump cone test. The use of vibration has been deemed appropriate because 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 an improvement on the slump test, it does not take into account the higher thixotropy of fiber-reinforced

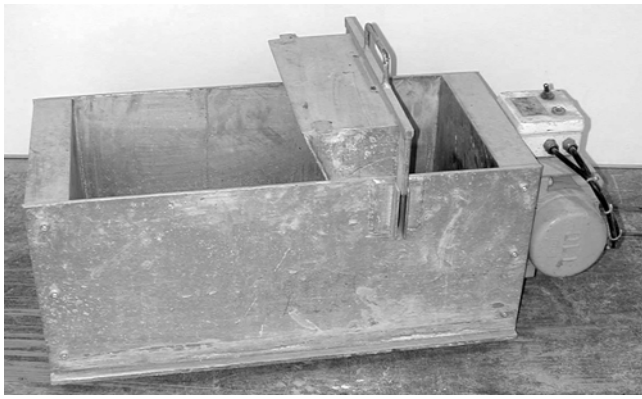


Fig. 3.14—LCL flow test.

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 50 mm (2 in.). More-fluid concretes can flow through the bottom of the cone, and cannot be measured with sufficient precision. The size of the apparatus also restricts the use of some concretes. The small gap of 38 mm (1.5 in.) 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) stated 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. To allow the use of readily available job equipment to conduct the test, the ASTM standard only specifies that the internal vibrator be 25 ± 3 mm ($1 \pm 1/8$ in.) 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 and positioning the vibrator and determining the correct start and stop times for the test. Because the concrete is not consolidated before 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; and
- The test apparatus consists of readily available equipment.

Disadvantages:

- The test is only appropriate for concrete mixtures with a slump of less than 50 mm (2 in.);
- The test is difficult to perform. Filling the inverted slump cone with concrete so that no concrete falls through the hole is not easy. 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; and
- Operator error is introduced in determining the exact stopping point of the test.

3.3.1.3.5 LCL flow test—The LCL flow test (Bartos 1992; Ferraris 1999; Bartos et al. 2002) is very similar to the angles flow box test. The test is suitable for concretes with high and moderate yield stress, and is not appropriate for concretes with very low or very high yield stress. The flow is assisted by vibration.

The device, pictured in Fig. 3.14, consists of a 150 x 600 mm (5.9 x 23.6 in.) rectangular box with a height of 150 mm (5.9 in.). An external vibrator is attached to one end. A triangular wedge holds uncompact 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.

Although the test provides a direct and usable result, the device needs to be calibrated using a standard aggregate and a standard mixture proportion 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 (1/2 in.). The larger device requires 35 L (1.25 ft³) of concrete.

Ferraris (1999) suggests that 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.

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; and
- 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; and
- The precise end point of the test can be difficult to determine.

3.3.1.3.6 Powers remolding test—The Powers remolding test (Powers 1968; Scanlon 1994; Wong et al. 2000) is similar to the Vebe consistometer. The test was developed by Powers and first presented in 1932. The test has been standardized by the U.S. Army Corps of Engineers as CRD-C 6-74 (1974).

The test apparatus consists of a 305 mm (12 in.) diameter cylindrical mold mounted on a standard apparatus, described in ASTM C124 (which was withdrawn in 1973). A

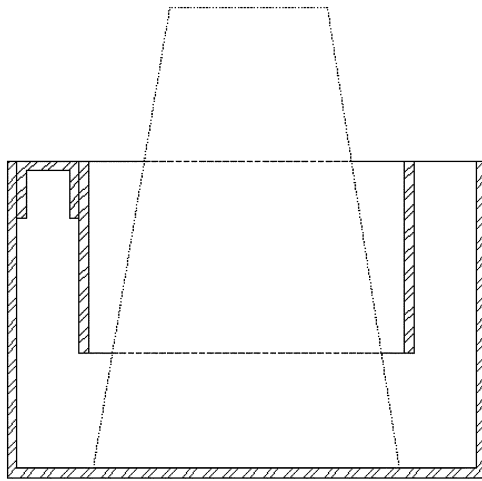


Fig. 3.15—Powers remolding test container incorporating inner ring.

separate 210 mm (8.25 in.) diameter ring is attached at the top of the cylinder, as shown in Fig. 3.15. 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 mixture. A mixture with high shear capacity easily passes under the ring, whereas mixtures with low shear capacity tend to clog and result in greater required remolding effort. It is possible that two mixtures 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).

Advantages:

- The Powers remolding test is a dynamic test and is suitable for high yield-stress concretes; and
- 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 high yield-stress concretes; and
- No analytical treatment or experimental testing of the test method has been performed to relate the test results to yield stress, plastic viscosity, or both.

3.3.1.3.7 Settlement column segregation test—The settlement column segregation test (Bartos et al. 2002; Rooney 2002; Sonebi et al. 2003) measures the degree of segregation that occurs in a concrete subjected to a standard settlement period and standard amount of jolting. The test method is primarily intended for highly-fluid concrete mixtures.

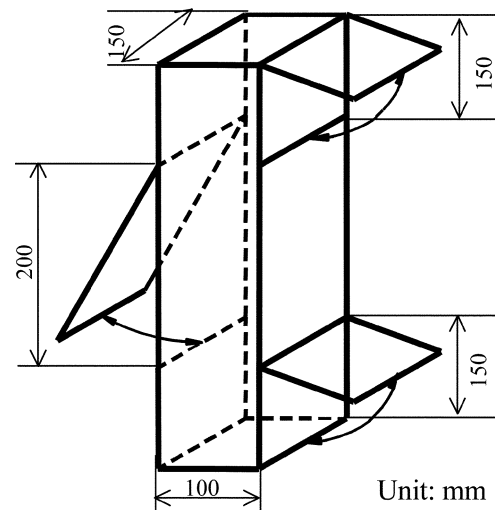


Fig. 3.16—Settlement column segregation test apparatus (1 mm = 0.039 in.).

The test apparatus consists of a tall, rectangular box mounted on top of a standard mortar drop table. The column, depicted in Fig. 3.16, is 500 mm (19.7 in.) tall and has cross-sectional dimensions of 100 x 150 mm (3.9 x 5.9 in.). 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 1 minute. The concrete is subsequently jolted 20 times in 1 minute using the drop table and then allowed to stand for an additional 5 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 bottom of the column are individually washed through a 5 mm (0.20 in.) sieve to leave only the coarse aggregate. The segregation ratio is then calculated as the 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.

The relative error of repeatability with 95% confidence limit for measuring the segregation ratio of fresh concrete is limited to 2 to 7% for no and mild dynamic segregation, and 12% for

Table 3.7—Dynamic segregation categories

Dynamic segregation category	Settlement ratio of fresh concrete SRFC
1. No segregation	0.96 and above
2. Mild segregation	0.95 to 0.88
3. Notable segregation	0.87 to 0.72
4. Severe segregation	0.71 and below

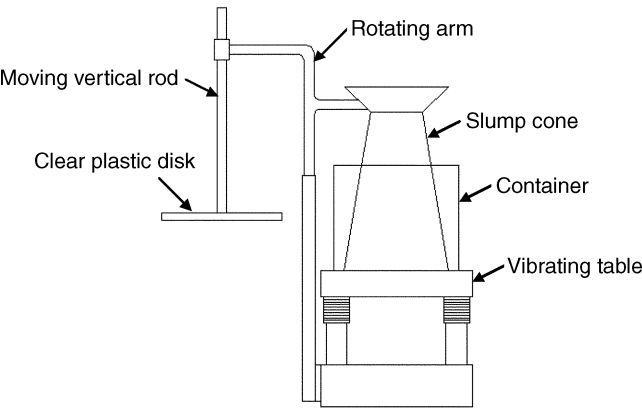


Fig. 3.17—Vebe consistometer.

notable dynamic segregation. For severe dynamic segregation, the relative error was higher, between 13 and 23%. The reproducibility of the segregation settlement column test was good. The coefficient of variation calculated from the results of four operators was between 4 and 8%. Four different dynamic segregation categories were defined for fresh SCC mixtures, as shown in Table 3.7 (Sonebi et al. 2007).

Advantages:

- The test attempts to simulate actual placement conditions; and
- 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; and
- The repeatability of test results decreases as segregation increases.

3.3.1.3.8 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 flowability.

The apparatus consists of a 10 L (0.35 ft³) 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 L (0.18 ft³) assists in determining the end of the test. Concrete is placed in the cylinder using the standard slump cone. For concretes with moderate flowability, the handle is allowed to fall from its vertical position and strike opposite sides of the container until the concrete remolds to the 5 L (0.18 ft³) mark on the container. For high yield-stress concretes, the number of drops of the table required to remold the sample to the 5 L (0.18 ft³) mark is recorded.

The Thaulow concrete tester is applicable mainly to high yield-stress concrete. ACI 211.3R recommends 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; and
- 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 too large and bulky for field use; and
- No analytical treatment or experimental testing of the test device has been performed to relate the test results to yield stress, plastic viscosity, or both.

3.3.1.3.9 Vebe consistometer—The Vebe consistometer (Bartos 1992; Scanlon 1994) 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 50 mm (2 in.).

The apparatus, shown in Fig. 3.17, consists of a metal cylindrical container mounted on a vibrating table producing a sinusoidal vibration. In the version of the test standardized in Europe as EN12350-3 (European Committee for Standardization 2000b), 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 concrete. The vibrating 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.

Juvas (1994) presented a modified Vebe test to more efficiently measure concretes that exhibit standard Vebe times greater than 30 seconds. In the modified Vebe test, a 20 kg (44 lb) 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 aforementioned procedure for use with roller-compacted concrete. Instead of placing concrete in a slump cone in the cylinder, concrete is placed directly into the 241 mm (9-1/2 in.) diameter, 197 mm (7-3/4 in.) tall cylinder without compaction. For Test Method A, a 22.7 kg (50 lb) 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 recorded. Both methods are applicable for concretes with maximum aggregate sizes up to 50 mm (2 in). A minimum of 22.7 kg (50 lb) of concrete is required for each test method.

Because the test apparatus is large and heavy, it is inappropriate for field use. The vibrating table should 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 mixtures are commonly used (Bartos 1992). The results are 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 by ASTM and identified by ACI 211.3R for proportioning low-slump concrete; and
- 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 high yield-stress concretes; and
- 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.

3.3.1.3.10 Vertical pipe apparatus—The vertical pipe apparatus (Tattersall and Baker 1989; Banfill et al. 1999) was developed as a laboratory device to measure the effects of vibration on fresh concrete.

The device, depicted in Fig. 3.18, consists of a 100 mm (4 in.) diameter, 700 mm (27.5 in.) 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 (2.8 in.) tall, and the gap between the block and the pipe is 60 mm (2.4 in.). 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.

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 Eq. (3-8), where b is the constant of proportionality expressing fluidity

$$\frac{dH}{dt} = -bH \quad (3-8)$$

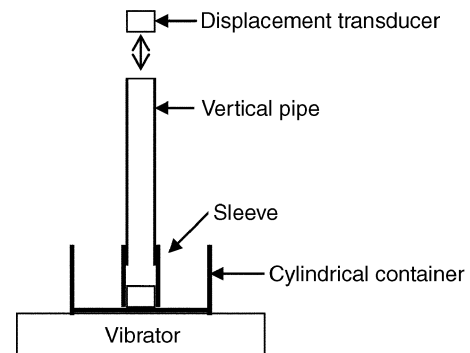


Fig. 3.18—Schematic of vertical pipe apparatus.

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; and
- 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 (2.4 in.) size of the opening below the pipe is too small for some aggregate sizes; and
- For highly flowable concretes, the concrete will quickly flow out of the pipe without the assistance of vibration.

3.3.1.3.11 Vibrating slope apparatus—Originally developed in the 1960s, the vibrating slope apparatus (Wong et al. 2000) was modified by the U.S. Army Engineering Research and Development Center (ERDC) for the U.S. Federal Highway Administration (FHWA). The device measures the workability of high yield-stress concretes subjected to vibration at two different shear rates to determine a workability index that is related to plastic viscosity and a yield offset that is related to yield stress. The researchers at the ERDC selected the vibrating slope apparatus over 20 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 ERDC is shown in Fig. 3.19. 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 apparatus is designed to be rugged and easily portable.