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# 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

Reported by ACI Committee 238

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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
$\alpha$ = time-dependent parameter
$\beta$ = constant
$\dot{\gamma}$ = shear rate
$\phi$ = concentration of solids
$\phi_m$ = maximum packing density
$\eta$ = viscosity of suspension
$[\eta]$ = intrinsic viscosity
$\eta_{pl}$ = plastic viscosity
$\eta_r$ = relative viscosity
$\eta_s$ = viscosity of the matrix
$\eta_\infty$ = apparent viscosity at very high shear rate
$\rho$ = density, kg/m$^3$
$\tau$ = shear stress, Pa
$\tau_o$ = yield stress not Bingham
$\tau_B$ = 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
$\tau$ = shear stress;
$\tau_B$ = yield stress;
$\eta_{pl}$ = 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** $\eta_{pl}$—(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** $\tau_B$—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;

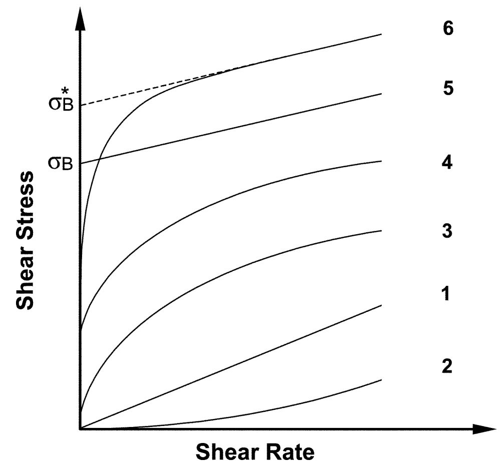



*Fig. 2.1—Identification of flow curves based on their characteristic shape.*

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 $\sigma_{app}$ has been exceeded;

5. **Bingham plastic (ideal)**—Obeys the Bingham relation ideally. Above the Bingham yield stress ($\sigma_B$ 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 ($\sigma_B$* 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

$\tau_0$ = yield stress (Pa);
$\eta_{pl}$ = 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;
$\alpha$ = time-dependent parameter; and
$\eta_\infty$ = apparent viscosity at very high shear rate.

**2.3.3** *Models predicting rheological properties of suspensions*

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

- Krieger-Dougherty model

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

where

$\eta$ = viscosity of the suspension;
$\eta_s$ = viscosity of the matrix;
$\eta_r$ = relative viscosity;
$\phi$ = concentration of solids;
$\phi_m$ = maximum packing density; and
$[\eta]$ = intrinsic viscosity defined as

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

# CHAPTER 3—TEST METHODS

## 3.1—Introduction

Since the early twentieth century, the concrete industry has recognized the need to monitor concrete workability to ensure that concrete can be properly placed and can achieve adequate properties in the hardened state. Numerous test procedures for determining workability have been developed for research, mixture proportioning, and field use. The vast majority of these test methods have never found any use beyond one or two initial studies. With the exception of the widely used slump test, the few methods that have been studied extensively have generally failed to gain widespread acceptance. Even with the increase in knowledge of concrete rheology, no test has been developed that is sufficiently compelling to convince the concrete industry to replace the slump test.

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

This section of the report describes 69 test methods that could be used for measuring concrete workability. While this list is not exhaustive, it includes most of the test methods that have been described in United States and western European literature. Many more tests have been developed for a single project or for a specific application, and have been sparsely reported in the literature, if at all. Despite the fact that many of the devices in this document will never be used and have been scarcely used in the past, an examination of tests that have failed and tests that have been supplanted by better tests is instructive in recognizing trends in concrete workability research and in selecting key concepts for the evaluation of new test methods.

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

## 3.2—Principles of measurements

The term "workability" is broadly defined; no single test method measures all aspects of workability. ACI Cement and Concrete Terminology (http://www.concrete.org/Technical/CCT/FlashHelp/ACI_Terminology.htm) describes workability as "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished." The Japanese Association of Concrete Engineers defines workability as "that property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed, and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials" (Ferraris 1999). Neville (1996) succinctly defines workability as "the amount of useful internal work necessary to produce full compaction." Workability depends not just on the properties of the concrete, but also on the nature of the application. A very dry concrete mixture, for example, may seem to have very low workability when it is, in fact, appropriate for the given application.

The focus of workability measurement has changed many times over the years. When the slump test was developed in the early twentieth century, concrete researchers were just beginning to recognize the importance of water content in predicting concrete strength (Wig 1912; Abrams 1922). The

**Table 3.1—Classes of workability measurement (Tattersall 1991)**

| | |
|---|---|
| *Class I: qualitative* (workability, flowability, compactability, finishability, pumpability) | To be used only in a general descriptive way without any attempt to quantify |
| *Class II: quantitative empirical* (slump, compacting factor, Vebe time, flow table spread) | To be used as a simple quantitative statement of behavior in a particular set of circumstances |
| *Class III: quantitative fundamental* (viscosity, mobility, fluidity, yield value) | To be used strictly in conformance with standard definitions |

slump test gives an indication of the water content and, thus, the strength of hardened concrete. The ability to improve strength by controlling concrete consistency represented a new advance for the concrete industry. The slump test was quickly adopted because of its simplicity (Abrams 1922). Still, the concrete industry quickly realized the slump test's inability to represent workability fully and, within several years of the introduction of the slump test, several attempts were made to develop better, more complete tests (Powers 1968). Although numerous test methods have been developed since the 1920s, not until research established concrete as a Bingham fluid did the principle of measuring concrete flow curves in terms of shear stress and shear rate emerge. Many of the new methods developed since the establishment of concrete as a Bingham fluid have attempted to measure yield stress non-Bingham and plastic viscosity.

The multitude of workability test methods can be divided into categories based on several different classification schemes. Tattersall (1991) broadly splits the assessment of workability into three classes, as shown in Table 3.1. The majority of workability test methods fall into Classes II and III.

Similar to Tattersall's scheme (1991), most test methods for workability have traditionally been split between single-point and multi-point tests. The concept of single-point versus multi-point tests is based on the flow curve relating shear stress and shear rate. A single-point test measures only one point on the flow curve and therefore provides an incomplete description of workability. For instance, the slump test only provides one point on the flow curve, namely, the yield stress. Multi-point tests, by contrast, measure additional points on the flow curve, typically by varying the shear rate, to provide a more complete description of concrete rheology. Single-point tests generally fall into Class II of Tattersall's scheme, whereas multi-point tests fall into Class III. Single-point tests can provide a direct or indirect measurement of yield stress, plastic viscosity, or some other properties. Multi-point tests typically measure yield stress and plastic viscosity, or closely related values. The existing test methods for concrete described in this document can be split between single-point and multi-point tests as shown in Table 3.2.

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

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

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

**Table 3.3—NIST categorization of concrete rheology test methods (Hackley and Ferraris 2001)**

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

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

Workability test methods have also been classified in terms of the type of flow produced during the test. In an effort to establish a uniform and widely accepted nomenclature for concrete rheology, the National Institute of Standards and Technology (NIST) divided existing rheology test methods into four broad categories (Hackley and Ferraris 2001). The definitions of the four categories are listed in Table 3.3.

## Table 3.4—Categorization of workability test methods*

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

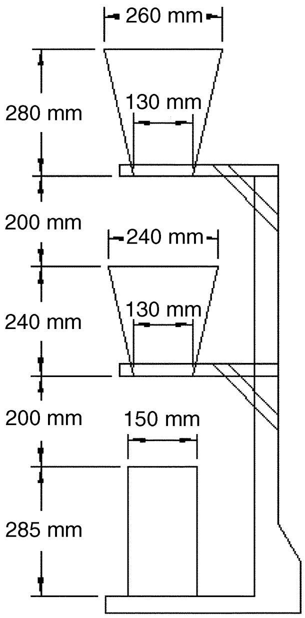



*Fig. 3.1—Standard version of compaction factor test apparatus (1 mm = 0.039 in.).*

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

**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 |

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;

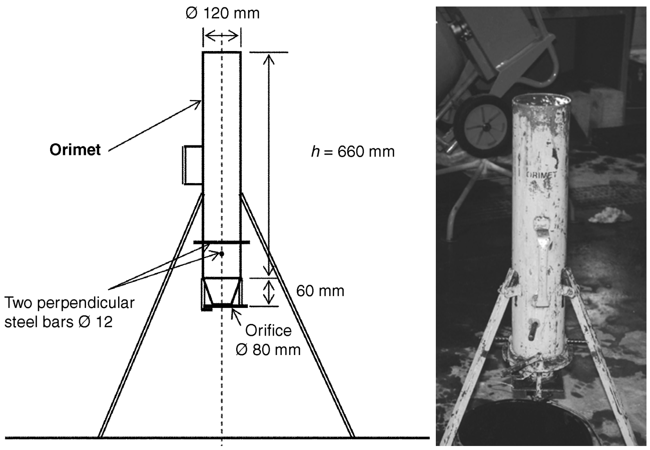



*Fig. 3.2—Modified Orimet for SCC (with two perpendicular bars) (1 mm = 0.039 in.).*

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 $ft^3$) 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 *r*, seconds | 0.7 | 1.6 | 2.9 | 4.6 | 6.6 |
| Reproducibility *R*, 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 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.

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

**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)

$$d = \frac{KW^n}{\theta} \tag{3-1}$$

where $W$ = cone mass, $\theta$ = 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.

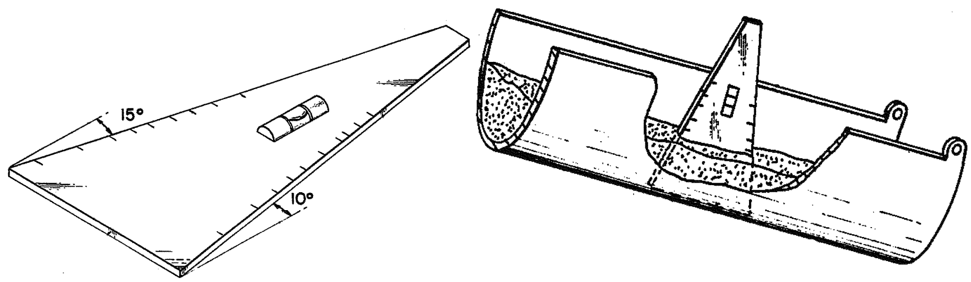



*Fig. 3.4—Delivery-chute depth meter (U.S. Patent and Trademark Office 1986).*

*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 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.

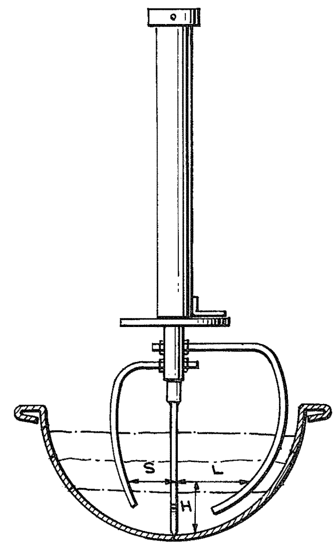



*Fig. 3.5—Delivery-chute torque meter (U.S. Patent and Trademark Office 1982a).*

*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 devices are required to determine slump.

*Disadvantages*:

- The torque meter is a single-point test that gives no indication of plastic viscosity. Readings are made at only one shear rate; 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 $ft^3$) 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 use. The test has never been used widely outside of the United States (Bartos 1992).

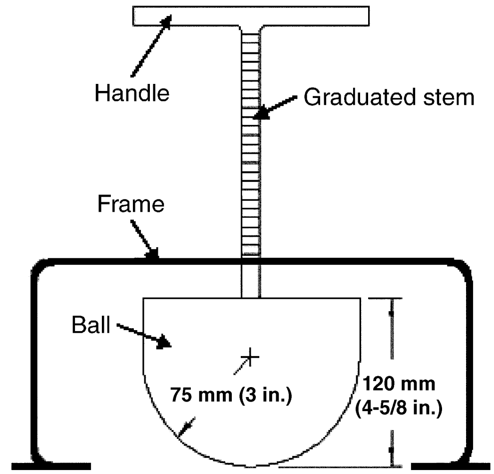



*Fig. 3.6—Kelly ball test apparatus.*

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 preformed 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

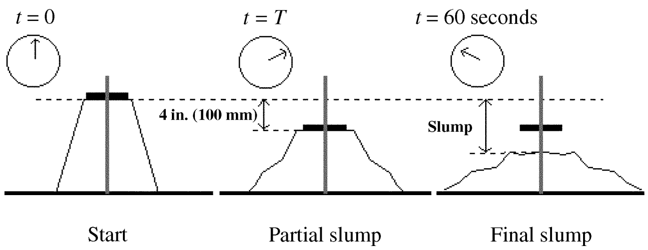



*Fig. 3.7—Schematic of modified slump test (Ferraris and de Larrard 1998).*

based on the results of the test. The yield stress ($\tau_o$, Pa) is expressed in terms of final slump ($s$, mm) and concrete density ($\rho$, kg/m$^3$), as shown in Eq. (3-2). The equation for yield stress is based on experimental measurement with the BTRHEOM rheometer

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

Plastic viscosity ($\mu$, 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

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

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

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 $\tau_y$ is a function of concrete density $\rho$ and the horizontal slump flow of the concrete *Sf*, as shown in Eq. (3-4)

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

where $g$ = gravity, $V$ = volume of the slump cone, and $\beta_1$ = 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)

$$\eta = \frac{gHV\rho}{150\pi(Sl)(Sf)^2}t_{slump} = \beta_2\frac{\rho}{(Sl)(Sf)^2}t_{slump} = \frac{\beta_2}{\beta_1}\frac{\tau_y}{(Sl)}t_{slump} \qquad (3\text{-}5)$$

where $H$ = height of slump cone mold, and $\beta_1$ = 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

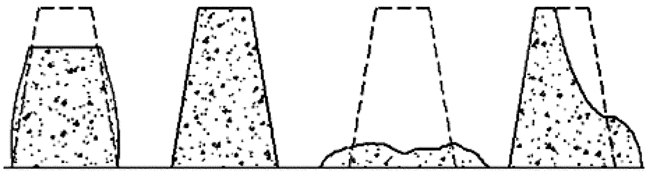



*Fig. 3.8—Four types of slump (not to scale).*

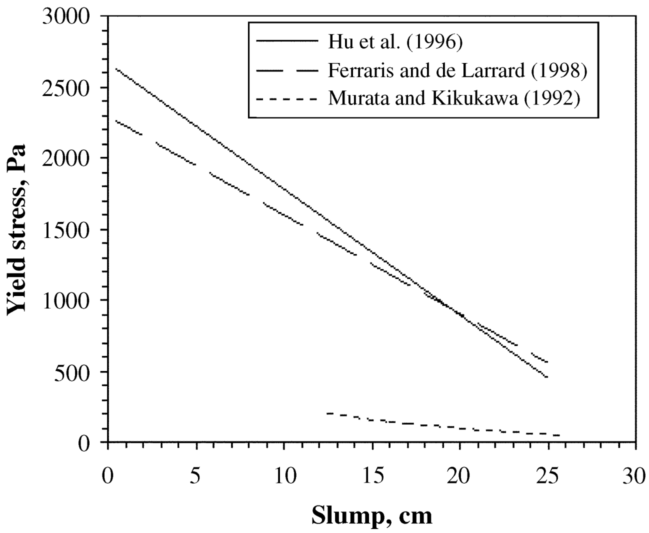



*Fig. 3.9—Comparison of equations relating yield stress and slump (1 cm = 0.39 in.; 1000 Pa = 0.145 psi).*

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.)

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

where $\tau_0$ = yield stress in Pa, $s$ = slump in mm, and $\rho$ = density in kg/m$^3$.

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)

$$\tau_0 = 714 - 473\log(s) \qquad (3\text{-}7)$$

where $\tau_0$ = 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, unless the rate of surface settlement after 30 minutes is employed to determine the static stability of the concrete.

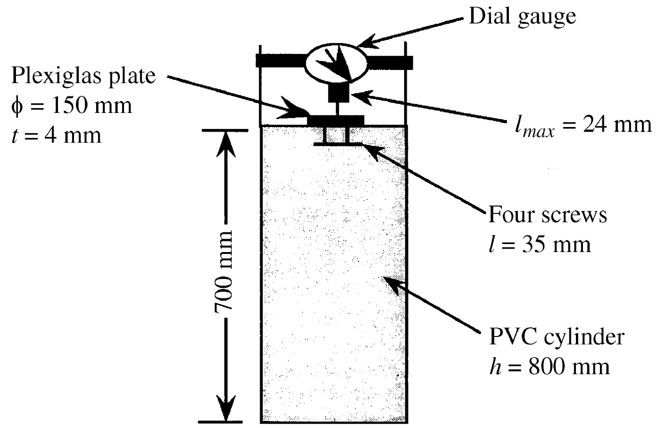



*Fig. 3.10—Surface settlement (Khayat 1999) (1 mm = 0.039 in.).*

**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

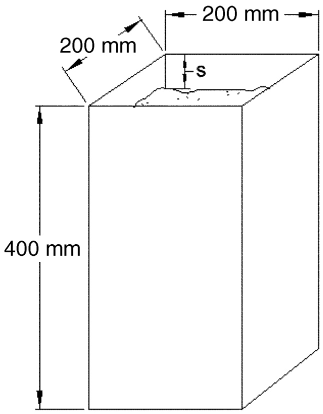



*Fig. 3.11—Compaction test apparatus (1 mm = 0.039 in.).*

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 (Deutches 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,

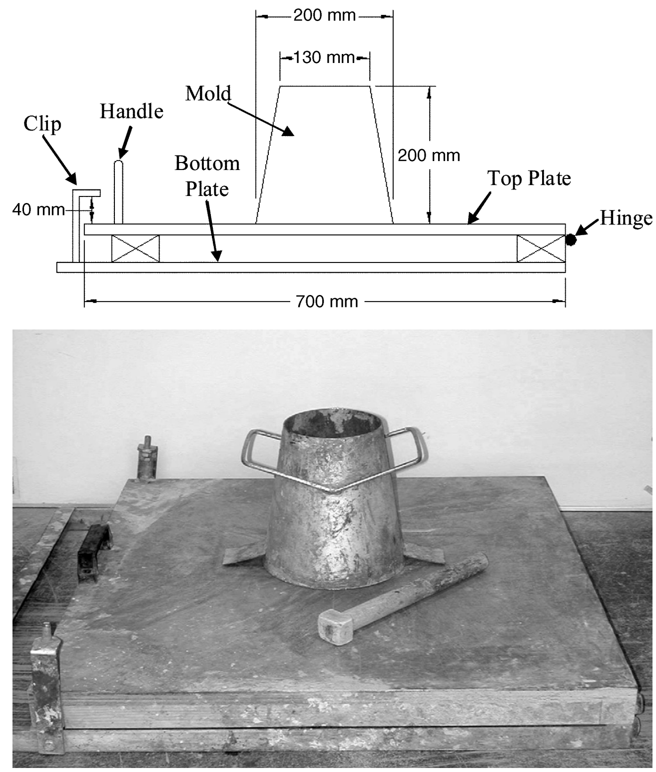



*Fig. 3.12—Flow table test apparatus (1 mm = 0.039 in.).*

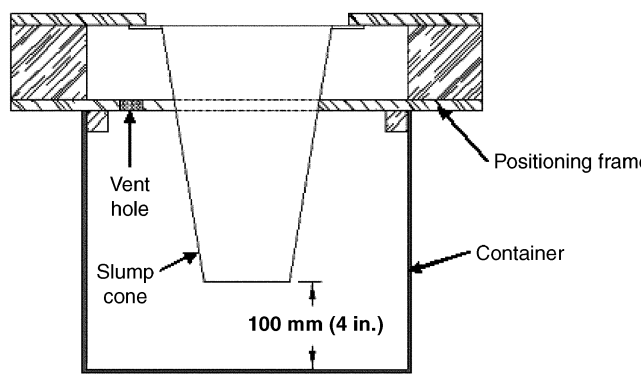



*Fig. 3.13—Inverted slump cone test apparatus.*

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 static tests that do not take into account the higher thixotropy of fiber-reinforced

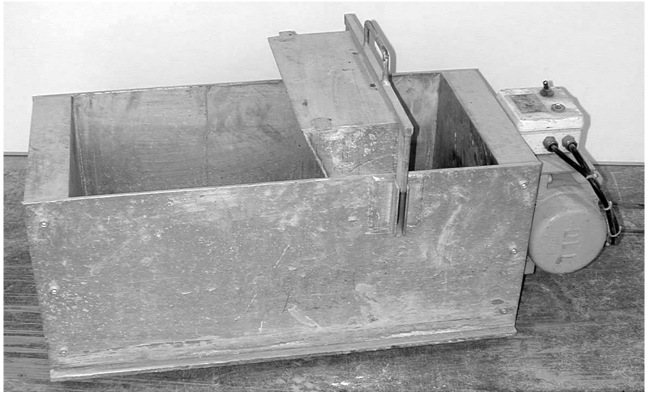


*Fig. 3.14—LCL flow test.*

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 ± 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 uncompacted concrete in the opposite end of the box. Rubber supports beneath the box isolate the box and absorb vibrations. To start the test, the wedge is removed and the vibrator is started. The time for concrete to spread to the other end of the box and fill to a line marked on the side of the box is measured.

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 $ft^3$) 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 drop table, described in ASTM C124 (which was withdrawn in 1973). A

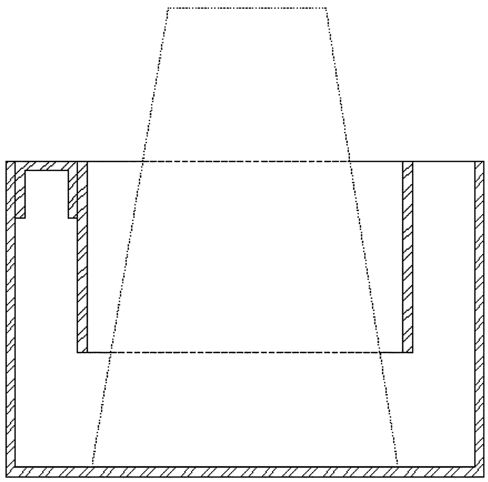


*Fig. 3.15—Powers remolding test container incorporating inner ring.*

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.

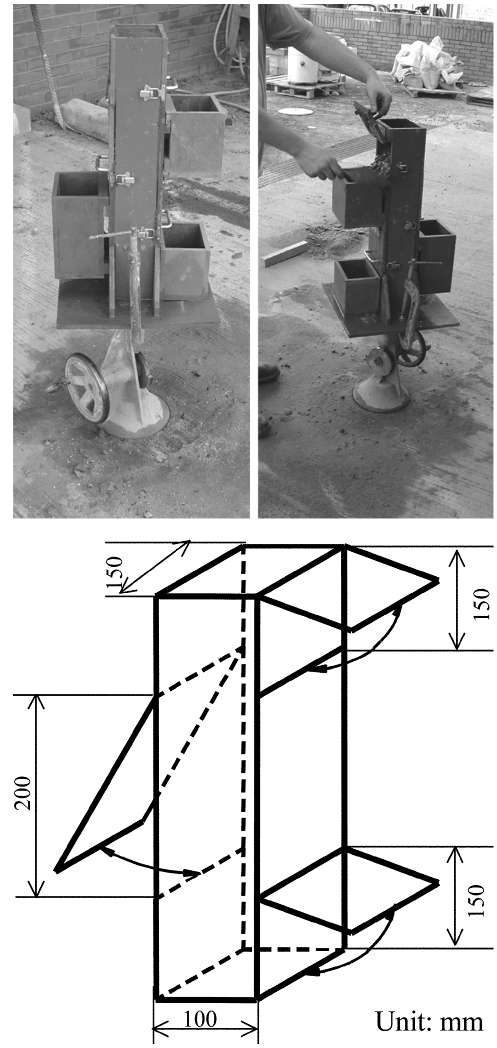



*Fig. 3.16—Settlement column segregation test apparatus (1 mm = 0.039 in.).*

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 SCC was 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 |

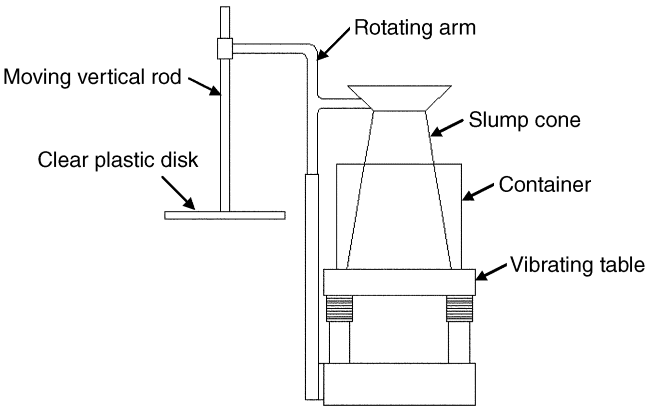



*Fig. 3.17—Vebe consistometer.*

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 $ft^3$) 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 $ft^3$) 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 $ft^3$) 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 $ft^3$) 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

$$\frac{dH}{dt} = -bH \tag{3-8}$$

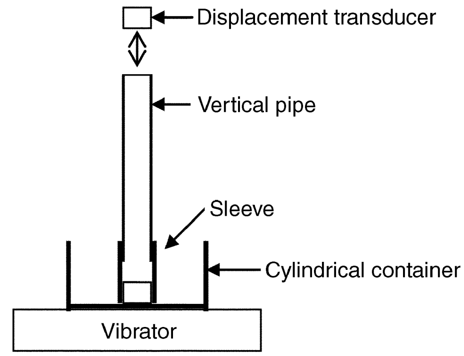



*Fig. 3.18—Schematic of vertical pipe apparatus.*

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 entire apparatus is designed to be rugged and easily portable.

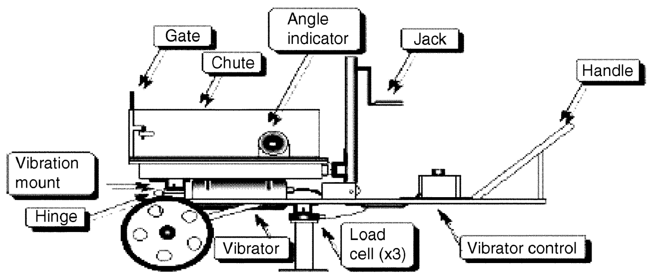



*Fig. 3.19—Vibrating slope apparatus (Wong et al. 2000).*

To operate the device, concrete is placed in the chute, which is set at a predefined angle (typically 10 to 15 degrees). The gate is opened and the vibrator is started, allowing concrete to fall from the chute into a bucket. The data from the load cells is used to calculate the discharge rate. Because the discharge rate generally decreases as concrete flows out of the chute, the maximum discharge rate is recorded. The test procedure is repeated a second time for a different incline angle. The results of the test are plotted as a graph of maximum discharge rate versus discharge angle. The straight line connecting the two data points is defined by Eq. (3-9)

$$R = WA + C \tag{3-9}$$

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

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

The ERDC researchers encountered multiple problems in developing the vibrating slope apparatus prototype. Many of the problems were trivial and easily corrected. Other problems will require further work to resolve. The test device is large, bulky, and weighs 160 kg (350 lb). The ERDC researchers give no cost information in their report.

*Advantages*:

- Unlike many rheometers, the device measures the workability of high yield-stress concretes; and
- The results of the device are given in terms of parameters related to yield stress and plastic viscosity.

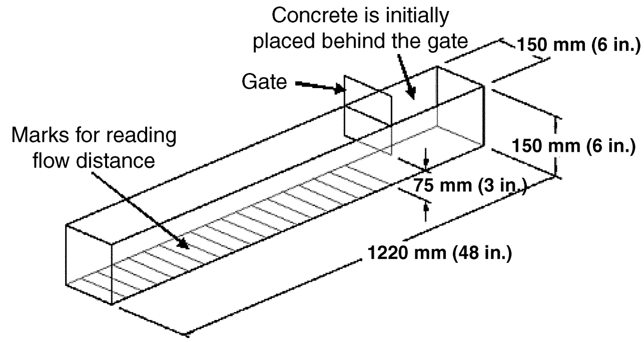



*Fig. 3.20—Vibratory flow meter.*

*Disadvantages*:

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

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

The test apparatus, shown in Fig. 3.20, consists of a 1220 mm (48 in.) long, 150 mm (6 in.) wide, and 150 mm (6 in.) tall box. A vertical gate approximately 1/4 of the length from one end of the box separates the box into two sections. To conduct the test, concrete is placed in the shorter portion of the box. The gate is opened to a height of 75 mm (3 in.) and a vibrator is inserted into the concrete in the shorter portion of the box. After 30 seconds, the vibrator is removed and the distance the concrete has traveled down the box is recorded.

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

*Advantages*:

- The test method is simple and provides a direct result; and
- The test apparatus consists of readily available equipment and materials.

*Disadvantages*:

- Preliminary test results indicate that the device is not effective in distinguishing between changes in mixture proportions; and
- The test results are dependent on the type of vibrator used. If an internal poker vibrator is used, the effect of vibration will change as concrete flows further away from the location of the vibrator.

**3.3.1.3.13** *Vibropenetrator*—The Vibropenetrator was developed by Komlos (1964) as a penetration test to better measure the behavior of vibrated concrete. The device consists of a standard 200 mm (7.9 in.) cube mold mounted on a vibrating table. Concrete is placed in the mold and compacted with the assistance of the vibrating table. A rod, guided by a sleeve mounted to the cube mold, is placed on top of the concrete. The vibrating table is started, and the time for the rod to penetrate a certain depth into the concrete is measured as an indication of workability. A ring on the rod touches the top of the sleeve to indicate the end point of the test. Komlos (1964) performed the test on moderate to low yield-stress concretes with water-cement ratios ranging from 0.38 to 0.90.

The results of the test are a function of not just the concrete properties, but also the nature of the applied vibration. The test is not appropriate for concrete containing large aggregates that could interfere with the descent of the rod.

*Advantages*:

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

*Disadvantages*:

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

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

The apparatus consists of cylindrical container mounted on a drop table. A removable lid placed atop the cylinder includes a hole that guides a graduated rod with an attached 50 mm (2 in.) ball vertically downward through the concrete. Concrete is placed into the container and compacted with eight drops of the table. The container is filled to the top and struck off level. The lid with the rod and ball is placed on top of the container. The number of drops required to lower the ball 200 mm (7.75 in.) into the concrete is recorded as a measure of consistency.

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

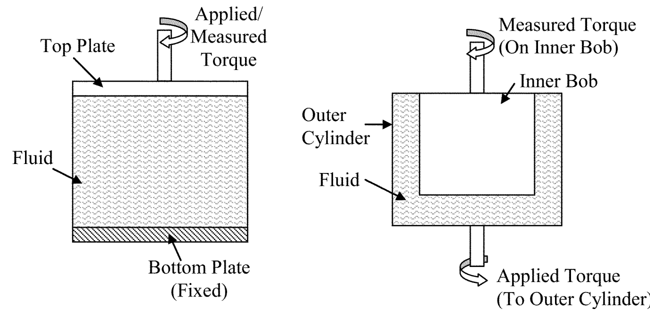



*Fig. 3.21—Schematic drawings of parallel plate rheometer (left) and coaxial cylinders rheometer (right).*

*Advantages*:

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

*Disadvantages*:

- To minimize the disproportionate effects of coarse aggregate particles on test results, the ball should be significantly larger than the maximum coarse aggregate size. Such a test device would be impractically large;
- Although the results of the test are related both to the yield stress and the plastic viscosity, results are not expressed in fundamental rheological units; and
- 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.

**3.3.1.4** *Rotational rheometers*—Many attempts have been made to adapt traditional rotational rheometers to measure concrete. Rotational rheometers for concrete apply shear stress to concrete specimens at various shear rates. From measurements of torque and rotation speed, the fundamental rheological parameters of yield stress and plastic viscosity, or closely related values, can be calculated. It must be cautioned, however, that the heterogeneous composition of concrete and practical restrictions on rheometer geometrical configuration limit the precision with which shear stress and shear rate can be computed. For instance, the local shear rate in the paste fraction is higher than the bulk shear rate assumed for computation of yield stress and plastic viscosity.

Although some rotational rheometers have been designed to be sufficiently small and rugged for use on job sites, the limited availability and high cost of most of these devices typically make them impractical for regular field use. Although different rotational rheometers measure different ranges of workability, various devices are available to measure nearly the full range of workability from high yield-stress concrete to SCC.

Rotational rheometers used for concrete feature parallel plate geometry, coaxial cylinders (also called Couette) geometry, or impeller geometry. A parallel plate rheometer and a coaxial cylinders rheometer are depicted schematically in Fig. 3.21. In a parallel plate rheometer, the fluid is sheared between two plates. The torque is applied and measured through one of the plates. In a coaxial cylinders rheometer, the fluid between an inner and outer cylinder is sheared. In a common arrangement of the coaxial cylinders rheometer, torque is applied to the outer cylinder, while the inner cylinder measures torque. In impeller rheometers, a vane or impeller inserted into the concrete rotates at various speeds in an axial or planetary motion.

In parallel plate and coaxial cylinders rheometers, rheological parameters, such as yield stress and plastic viscosity, can be calculated in fundamental units directly from the torque and rotation speed test data and the rheometer geometry. In impeller rheometers, however, rheological parameters cannot be calculated in fundamental units directly. Therefore, standard calibration fluids are used to establish the relationships between the measured torque and rotation speed data and rheological parameters in fundamental units. Instead of establishing such a calibration, the slope and intercept of the torque and rotation speed data are used as rheological parameters in nonfundamental units.

While rheometers have traditionally been used successfully for fine particle suspensions, concrete presents unique challenges. Concrete rheometers deal with the large size of coarse aggregates, concrete segregation, and time dependence of flow properties. For instance, to maintain a homogenous sample during testing, the difference between the inner and outer cylinder radii should be at least five times the maximum aggregate size. Further, the ratio of the outer cylinder radius to the inner cylinder radius should be 1.0 to 1.1 (Ferraris 1999). Rheometers constructed based on these particular requirements are generally too large to be practical. Indeed, many of the problems with rotational rheometers have yet to be overcome. Calculated values of shear rate and shear stress within the concrete in a rheometer are necessarily approximations. Due to these limitations and other differences between rheometer designs, the values measured by different rheometers for the same concrete may vary considerably. Accordingly, it is not possible to establish a single, fully accurate result for a given concrete mixture. While the values recorded by different rheometers may vary in absolute terms, correlations can often be established.

Three of the test methods described in this section—soil direct shear test, mixer devices, and fresh concrete tester—incorporate some concepts of traditional rotational rheometers, but do not measure concrete at different shear rates. These devices only determine consistency, and provide no indication of plastic viscosity.

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

The Bertta apparatus features traditional coaxial cylinders geometry with outer and inner cylinders that are 480 and 330 mm (18.9 and 13.0 in.) in diameter, respectively, and 400 mm (15.7 in.) in height. Vanes attached to the outer and inner cylinders act to prevent slip. Unlike other coaxial cylinders rheometers used for concrete, the outer cylinder operates in an oscillatory mode with a set frequency and amplitude. The stationary inner cylinder measures torque. During the test, a vertical pressure can be applied to the concrete sample. The change in height of the concrete sample during the test is recorded as a measure of the compactability of concrete when subjected to shear compaction.


*Fig. 3.22—BML viscometer (left) with an enlarged view of inner blades (right).*

The geometry of the device presents problems with accurately measuring rheological parameters. Specifically, the gap between the cylinders limits the maximum aggregate size to 13 mm (1/2 in.) based on the gap size being five times the maximum aggregate size. The ratio of the outer cylinder radius to the inner cylinder radius is too large for a linear flow gradient.

*Advantages*:

- The operation of the device is automated;
- The device measures torque at various rotations speeds, which allows the calculation of plastic viscosity and yield stress;
- The test results can be computed in fundamental units of rheology; and
- The device can be used to measure a wide range of concrete workability, including zero-slump concretes and highly workable concretes.

*Disadvantages*:

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

**3.3.1.4.2** *BML viscometer*—The BML viscometer (Wallevik 1990, 2003; Wallevik and Gjørv 1998) is based on the design of a coaxial cylinders rheometer. The BML viscometer was developed in Norway in 1987.

The BML viscometer is shown in Fig. 3.22. The outer cylinder, which rotates during the test, features a series of vertical ribs. Instead of an inner cylinder, a series of vertical blades, which remained stationary during the test, is used. The torque acting on the inner blades is recorded during the test. The sizes of the inner blades and outer cylinder can be changed based on the size of the aggregate in the concrete being tested. At a constant angular velocity, the shear rate in the concrete is nonuniform at the bottom of the outer cylinder. Therefore, to measure torque more accurately, the inner blades are split into three parts so that only the middle section of each inner blade measures torque. The concrete near the middle section of the inner cylinder is subject to two-dimensional shearing, whereas the concrete in the bottom of the outer cylinder is subject to complex three-dimensional shearing. The device is operated at various fixed speeds. The cylinders are mounted on a much larger unit that houses the mechanical equipment. A computer software package converts the output data to values for flow resistance *G* and relative viscosity *H*, which can then be related to yield stress and plastic viscosity, respectively, based on the Reiner-Rivlin equation. For measurements where a portion of the concrete in the rheometer annulus is at a stress below the yield stress and does not flow, the data are discarded. Only flow curve points where all concrete in the rheometer annulus flows are used to compute yield stress and plastic viscosity.

The BML viscometer is intended for flowable concretes with slumps greater than 120 mm (4.7 in.), and can be used for SCCs. The device has also been used successfully for concretes with slumps as low as 50 mm (2 in.). For lower-slump concretes, the inner cylinder can be replaced with a blade impeller system similar to the one used in the Tattersall two-point device. The device should be calibrated with external weights or calibration oils.

The BML viscometer has been commercially available since 1992 as the ConTec viscometer. From 1992 to February 2001, approximately 30 devices were sold (Ferraris and Brower 2001).

*Advantages*:

- The device measures torque and at various rotations speeds, which allows the calculation of plastic viscosity and yield stress;
- The operation of the device is automated;
- The test results can be computed in fundamental units of rheology; and
- The device is appropriate for a wide range of concrete workability, although some accuracy is lost in measurements of highly flowable concrete mixtures and high yield-stress concrete mixtures.

*Disadvantages*:

- The device is too large to be used outside of a laboratory;
- The device is complex and expensive; and
- Concrete in the shearing zone between the inner and outer cylinders has a tendency to dilate, resulting in artificially low measurements of torque.

**3.3.1.4.3** *BTRHEOM rheometer*—Developed in France, the BTRHEOM (de Larrard et al. 1997; de Larrard 1999; Wong et al. 2000; Ferraris and Brower 2001; Bartos et al. 2002) is a parallel plate rheometer for concrete.

The device, pictured in Fig. 3.23, consists of a 240 mm (9.4 in.) diameter, 100 mm (3.9 in.) tall cylindrical container. Blades are mounted at the top and bottom of the container. The bottom blade is fixed, while the top blade rotates and measures torque. The motor is housed below the container, and is connected to the top blade through a 40 mm (1.6 in.) diameter inner shaft in the concrete container. The device includes a vibrator to consolidate the concrete and to measure the effect of vibration on the rheological parameters. The test is conducted by turning the top blade at different speeds and recording the resulting torque. Computer software developed for the BTRHEOM automatically calculates results in terms of the Bingham or Herschel-Bulkley models.

*Fig. 3.23—BTRHEOM rheometer.*

The BTRHEOM is capable of measuring dilatancy during a test. To do so, a plate is set on top of the concrete. As the concrete expands in volume during the test, the upward displacement of the plate is recorded. In addition to calculating the yield stress $\tau_0$, the yield stress at rest can be determined using a stress-controlled test. Since the initial development of the BTRHEOM, the accuracy of the device has been validated experimentally and analytically (Hu et al. 1996). A modified version of the BTRHEOM has been developed to eliminate several drawbacks of the original device (Szecsy 1997; Struble et al. 2001). In this version, the motor is located above the bowl; as a result, fewer parts are necessary. Instead of using two felt seals that need to be replaced frequently, the simplified version only requires a single rubber o-ring.

*Advantages*:

- The device measures torque at various rotations speeds, which allows the calculation of plastic viscosity and yield stress;
- The test results can be computed in fundamental units of rheology;
- The device can measure dilatancy and can compute yield stress at rest;
- The results of the test have been verified with finite element models;
- The operation of the device is computer controlled, requiring little user intervention; and
- A built-in vibrator allows the measurement of rheological properties under vibration.

*Disadvantages*:

- The device is complex and expensive;
- The seals need to be replaced frequently. The device must be recalibrated to account for the friction caused by new seals;
- Although the device is designed to be compact and sufficiently rugged for field use, the device is too expensive for everyday field use;

- The device does not measure high yield-stress concretes (generally with slumps less than 100 mm); and
- The device is not a true parallel plate rheometer. The calculations of shear stress and shear rate (and yield stress and plastic viscosity) are only approximate because they ignore the discontinuity in flow at the boundary of the moving and stationary parts of the cylinder.

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

Because the CEMAGREF-IMG was not initially intended to measure the rheology of concrete, it is significantly larger than other rheometers. In fact, the large size of the device makes it impractical for measuring concrete. The outer cylinder is 1.2 m (47.2 in.) in diameter and 0.9 m (35.4 in.) tall, while the inner cylinder is 0.76 m (29.9 in.) in diameter. The rheometer holds 500 L (17.7 $ft^3$) of concrete, and is mounted on a trailer. The inner cylinder rotates and measures torque, while the outer cylinder remains stationary. Blades on the outer cylinder and a metallic grid on the inner cylinder reduce concrete slippage. Because the inner cylinder is mounted within the outer cylinder from the bottom instead of from the top, a rubber seal is provided at the base of the inner cylinder to ensure that all concrete remains within the gap between the cylinders. The torque on the inner cylinder at various rotation speeds is logged and used to calculate yield stress and plastic viscosity.

Although the large size of the CEMAGREF-IMG allows the testing of concrete mixtures with large maximum aggregate sizes, the ratio of the outer radius to the inner radius is too large. As a result, a region of no flow occurs within the annulus as the concrete near the inner cylinder is sheared, while the shear stress applied to the concrete near the outer cylinder is insufficient to overcome the yield stress of the concrete. The large size of the CEMAGREF-IMG also makes the device impractical to transport.

*Advantages*:

- The device measures torque at various rotations speeds, which allows the calculation of plastic viscosity and yield stress;
- The test results can be computed in fundamental units of rheology; and
- The size of the device accommodates large maximum aggregate sizes.

*Disadvantages*:

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

**3.3.1.4.5** *Concrete truck mixer as rheometer*—The mixer devices described previously only allow the determination of one parameter; however, the possibility of determining two parameters—analogous to yield stress and plastic viscosity—by monitoring mixing torque at various rotation speeds has also been explored. Daczko (2002) published data, and Amziane et al. (2005) performed systematic testing comparing the data obtained from the truck with data from a rheometer.

To transform a truck mixer into a rheometer requires that at least two entities be measured: rotational speed of the drum and the power consumption or torque used by the mixer motor during rotation. To obtain both the yield stress and the viscosity, it is necessary to obtain data at several speeds. The methodology proposed by Amziane et al. (2005) requires the measurement of the power during mixing, the load volume, the mass of concrete, and the shear rate in the concrete, which is deduced from the drum rotational speed and geometrical characteristics. The calculation method to determine the shear rate in the drum from the speed and the truck geometrical characteristics was developed in Helmuth et al. (1995). Given the complex geometrical characteristics of mixing trucks, this calculation is difficult, if not impossible, to accomplish precisely.

The values of these two variables (power and rotation speed) at different speeds may be plotted against each other. If it is assumed that power is directly proportional to stress and rotation speed directly proportional to shear rate, the slope of this resulting curve according to the Bingham model will give the plastic viscosity, and the intercept at zero shear rate will give the yield stress. The concrete truck mixer used needs to be fitted with a device capable of measuring the oil pressure to turn the drum (also called slump meter). The drum speed measurements could be manually made using a stopwatch, or an automatic system could be designed. The Bingham test involves sweeping shear rates from high to low and measuring the stress at various shear rates. Therefore, the drum should be turned at the highest possible speed, usually 1.67 rad/s (16 rpm), and then gradually decreased in discrete steps to zero while the oil pressure is measured.

*Advantages*:

- The measurements can be done before the concrete is discharged;
- The device measures torque at various rotations speeds, which allows the calculation of plastic viscosity and yield stress (nonfundamental units);
- The operation of the device could be automated; and
- The device is applicable to a wide range of concrete workability.

*Disadvantages*:

- The results for yield stress and plastic viscosity are not given in fundamental units (Pa and Pa·s, respectively);
- The correlation between rheometer data and the truck-obtained results was not completely proven as yet;
- A protocol to develop a relationship with any truck needs to be developed; and
- More research is needed for this method to be fully operational.

**3.3.1.4.6** *Consolis RheoMixer®*—The Consolis RheoMixer® (patent pending), developed by Consolis Technology, is a workability measurement system for normal concrete and SCC for on-line process control in full-scale production.

The system measures the workability of concrete in a planetary mixer during mixing. The system determines the rheological properties of the concrete mixture by changing the rotational speed of the mixer motor and measuring the torque at each speed. The control of the speed is accomplished by a frequency inverter, which also measures the motor torque.

The system has been implemented in planetary mixers in precast plants in Finland and in Sweden. The size of the mixers varied from 1.5 to 3.0 $m^3$ (2 to 4 $yd^3$).

*Advantages*:

- The device measures torque at various rotation speeds, which allows the calculation of plastic viscosity and yield stress;
- The system measures the average properties of the whole batch;
- The measurement sequence can be adjusted freely;
- No sample handling is required;
- No manual work is required, which reduces testing labor costs;
- No extra cleanup of the device is required;
- The result can be used for online control of workability; and
- The soft start of the mixer reduces maintenance costs.

*Disadvantages*:

- The mixing time is prolonged in some cases;
- The device does not give results in fundamental units without calibration;
- A continuous signal of the rheological parameters is not available;
- The installation of the system requires replacement of existing power cables and new power switches; and
- The initial equipment cost is high relative to empirical tests such as the slump test.

**3.3.1.4.7** *CONVI Visco-Probe*—The CONVI Visco-Probe (patent pending) is a device for measurement of normal concrete and SCC workability in a concrete mixer during mixing. The system has been implemented in planetary mixers in ready-mix and precast plants in Denmark and in Sweden.

The system, which is shown in Fig. 3.24, consists of a steel sphere attached to a rod, which in turn is attached to a moving part of the mixer. The diameter of the sphere is 100 mm (4 in.), and the length of the rod is 500 mm (20 in.). Other rod lengths are available. Due to the varying relative movement of the sphere in relation to concrete during the mixing in a planetary mixer, the resistance to the movement varies. This resistance is continuously measured by a torque transducer in the rod and transmitted by a wireless connection to a computer where a computer program evaluates the signal by finding the highest and lowest value during a cycle. These values are used for calculation of plastic viscosity and yield stress.

In a planetary mixer, the speed of the sphere in relation to the concrete varies because of the planetary motion. By adjusting the position of the sphere, a suitable ratio between highest and lowest relative speed can be obtained. In a pan mixer, two probes are needed to measure resistance at two different speeds.

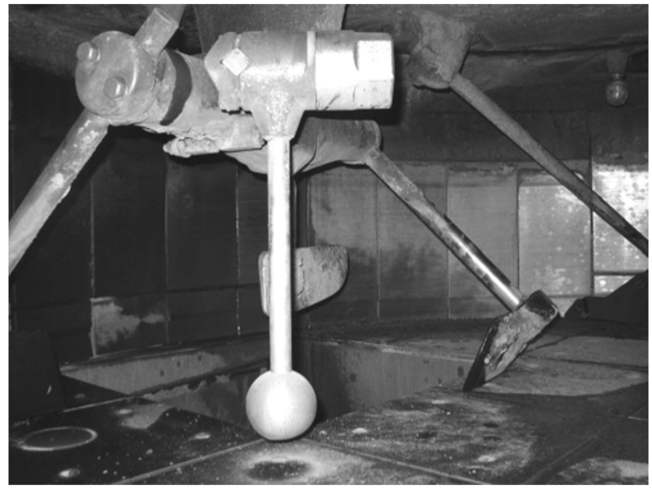


*Fig. 3.24—CONVI Visco-Probe.*

*Advantages*:

- The device measures torque at various rotation speeds, which allows the calculation of plastic viscosity and yield stress;
- The system measures the average properties of the entire batch;
- No sample handling is required;
- No manual work is required, which reduces testing labor costs;
- No extra cleanup of the device is required; and
- The result can be used for online control of workability.

*Disadvantages*:

- The device does not give results in fundamental units without calibration (for example, Pa and Pa·s);
- The installation of the system sometimes requires removal of a mixer blade;
- The battery of the torque sensor needs to be replaced regularly; and
- The initial equipment cost is high relative to empirical tests such as the slump test.

**3.3.1.4.8** *FHPCM*—The flow of high-performance concrete meter (FHPCM) was developed specifically for measuring highly flowable concrete mixtures (Yen et al. 1999; Tang et al. 2001). The rheometer has been used successfully for concretes with slumps of 140 to 280 mm (5.5 to 11 in.).

The FHPCM features coaxial cylinders geometry. The outer cylinder is 225 mm (8.9 in.) in diameter and 170 mm (6.7 in.) in height. The inner spindle is 150 mm (5.9 in.) in diameter, 150 mm (5.9 in.) in height, and is set 20 mm (0.8 in.) above the bottom of the outer cylinder. The inner spindle rotates, while the outer cylinder remains fixed. Ribs attached to the outer cylinder prevent slip. The rotation speed of the inner spindle is reduced from an initial maximum value in a stepwise fashion. The torque required to turn the spindle is considered the sum of the torque in the annulus (area between the outer and inner cylinders) and the torque in the space under the bottom of the spindle. The torque in the annulus and in the space below the spindle can be described with equations for coaxial cylinders rheometers and parallel plate rheometers, respectively. From these equations, the yield stress and plastic viscosity can be calculated in fundamental units. The device is calibrated using a fluid of known flow properties. Yen et al. (1999) used a malt sugar solution with known properties, as measured with an established traditional coaxial cylinders viscometer.

The geometry of the FHPCM is problematic. The ratio of the outer cylinder radius to the inner cylinder radius is 1.51. The maximum aggregate size that can be tested, based on the gap size between the inner and outer cylinders being at least five times the maximum aggregate size, is 7.6 mm (0.3 in.). In research conducted using the FHPCM (Yen et al. 1999), the maximum size of aggregate used was 12.7 mm (1/2 in.).

*Advantages*:

- The device measures torque and at various rotation speeds, which allows the calculation of plastic viscosity and yield stress; and
- The operation of the device is automated.

*Disadvantages*:

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

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

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

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

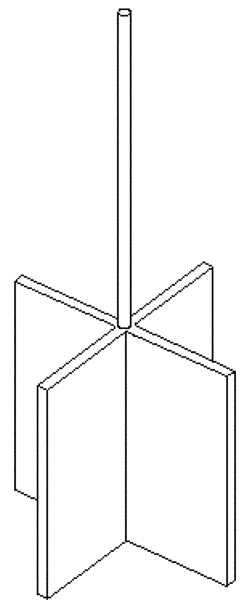


*Fig. 3.25—ICAR rheometer vane (Koehler 2004).*

*Advantages*:

- The device allows for fast and continuous measurement of workability; and
- The embedded electronic interface allows for the instant correlation of test readings to slump. The results can be logged for documentation purposes.

*Disadvantages*:

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

**3.3.1.4.10** *ICAR rheometer*—The International Center for Aggregates Research (ICAR) rheometer (Koehler 2004) is a low-cost, portable rheometer intended for concrete mixture proportioning, research and development, and field quality control. It has been used successfully to test concretes with workability ranging from a slump of approximately 75 mm (3 in.) to SCC.

The ICAR rheometer is approximately the size of a hand-held drill and includes a four-bladed vane impeller that is immersed into concrete. The typical vane, as shown in Fig. 3.25, is 125 mm (5 in.) in diameter and 125 mm (5 in.) in height. The operation of the rheometer is fully automated by software that controls the operation of test, records test data, and computes test results.

The ICAR rheometer can be used to perform a stress growth test or measure a flow curve. In a stress growth test, the vane is rotated at a constant, low speed while the buildup in torque acting on the vane is monitored. The peak torque is used as one measure of the yield stress. In a flow curve test, the vane is rotated at a series of fixed speeds, either in ascending or descending order, and the torque acting on the vane is measured. The resulting torque and rotation speed data are used to compute test results. The use of two yield stress measurements—from the stress growth test and the flow curve test—indicates both the shear stress needed to initiate flow from rest (stress growth test) and the shear stress needed to maintain flow once flow has been initiated (flow curve test).

*Advantages*:

- The device measures torque at various rotations speeds, which allows the calculation of plastic viscosity and yield stress;
- Due to its low cost and portability, the ICAR rheometer is well-suited for routine job-site quality-control measurements;
- The operation of the test is fully automated;
- The test can be conducted quickly; and
- In addition to measuring a flow curve, the ICAR rheometer can also be used to perform a stress growth test.

*Disadvantages*:

- The rheological parameters measured by the ICAR rheometer are not well understood in practice, particularly when compared with the slump test; and
- The sample size needed to obtain representative results is relatively large.

**3.3.1.4.11** *IBB rheometer*—The IBB rheometer (Beaupre and Mindess 1994; Ferraris and Brower 2001; Bartos et al. 2002) is a modification of the Tattersall two-point device. Although the IBB rheometer was originally developed to measure the rheology of wet-mix shotcrete, it has been successfully used on a wide range of concretes, from concretes with a slump of 20 mm (3/4 in.) to SCCs.

The device consists of a rotating impeller inserted into a fixed cylindrical container. When testing concrete, a fixed container with dimensions of 360 x 250 mm (14.2 x 9.8 in.) is used. A smaller container with dimensions of 230 x 180 mm (9.1 x 7.1 in.) can be used for mortars. A computer-controlled DC motor turns an H-shaped impeller capable of rotating either in a planetary motion or in an axial rotation. For concrete, a 50 mm (2.0 in.) gap is left between the impeller and the sides and bottom of the container. When the mortar setup is used, a 25 mm (1.0 in.) gap exists between the impeller and the container. Based on these dimensions, the maximum aggregate size is 25 mm (1.0 in.) for concrete samples, and 12 mm (1/2 in.) for mortar samples.

A load cell measures the reaction torque from the impeller, while a tachometer measures the impeller's rotation speed. Like the Tattersall two-point device, the linear relationship between torque and speed is defined by the slope $h$ and the zero speed intercept $g$. The values of $g$ and $h$ are calculated automatically by the computer and displayed at the end of the test. The $g$ and $h$ values are not uniquely related yield stress and plastic viscosity because of the possibility of turbulent flow and because rotation speed and torque are not directly proportional to shear rate and shear stress, respectively.

**Table 3.8—United States patented devices to measure workability of concrete in mixer**

| Patent no. | Date issued | Patent title |
|---|---|---|
| 1,730,893 | Oct. 8, 1929 | Method of and apparatus for determining consistency of concrete |
| 1,898,890 | Feb. 21, 1933 | Concrete mixometer |
| 1,980,184 | Nov. 13, 1934 | Control recording apparatus |
| 2,013,837 | Sept. 10, 1935 | Consistency and time indicating and recording equipment for concrete mixers |
| 2,409,014 | Oct. 8, 1948 | Mixture consistency indicator for concrete mixers |
| 2,629,790 | Feb. 24, 1953 | Apparatus for measuring and/or controlling the consistency of a paste or slurry |
| 2,643,542 | June 30, 1953 | Apparatus for determining consistency of concrete mixture |
| 2,821,079 | Jan. 28, 1958 | Apparatus for measuring the consistency during mixing of concrete |
| 3,237,437 | Mar. 1, 1966 | Slump meter |
| 3,403,546 | Oct. 1, 1968 | Slump indicator for concrete |
| 3,631,712 | Jan. 4, 1972 | Method and apparatus for determining slump in concrete |
| 3,640,121 | Feb. 8, 1972 | Slump indicator |
| 3,924,447 | Dec. 9, 1975 | Slump indicator |
| 4,356,723 | Nov. 2, 1982 | Process and apparatus for continuously measuring slump |
| 4,900,154 | Feb. 13, 1990 | Concrete mixer having means for determining consistency of concrete mixing therein |
| 6,227,039 | May 8, 2001 | System and method for controlling concrete production |

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

*Advantages*:

- The operation of the device is automated;
- The device measures torque at various rotations speeds, which allows the calculation of plastic viscosity and yield stress; and
- The device is applicable to a wide range of concrete workability.

*Disadvantages*:

- The device does not allow the direct calculation of yield stress and plastic viscosity in fundamental units. Instead, $g$ and $h$ values are computed;
- The device, in its current form, is too large for field use, although a version on wheels is available. The volume of concrete required for the test is larger than most other rheometers; and
- Like the Tattersall two-point device, segregation can occur over the duration of the test, even when the particular concrete mixture would not be susceptible to segregation in actual placement conditions.

**3.3.1.4.12** *Mixer devices*—Multiple devices have been developed to measure the consistency of concrete while still in a mixer. Although the testing principle and apparatus vary for each test method, the general objective of each test method is to measure the workability of concrete continuously before it is discharged from the concrete mixer. Such devices that have been patented in the United States are listed in Table 3.8. Although the test methods resemble rotational

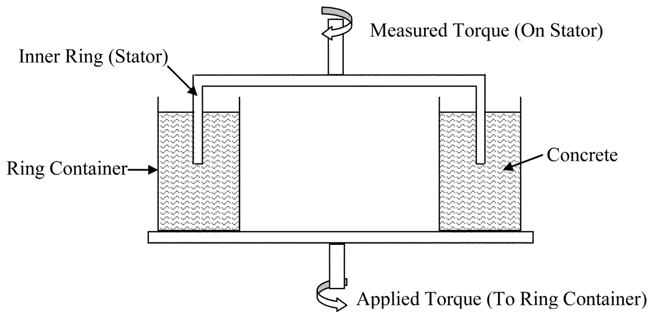



*Fig. 3.26—Revised recording plastometer (not to scale) (after Powers [1968]).*

rheometers, they typically only measure a single parameter, not yield stress and plastic viscosity.

As Table 3.8 indicates, devices to measure the workability of concrete in a mixer have been developed over a nearly 70-year period. One of the most recent devices, the ready-mix truck hydraulic device (U.S. Patent and Trademark Office 1982a; Wong et al. 2000) measures the torque required to turn the mixer on a ready-mix truck and correlates this torque reading to slump. Because each truck can be different, correlations need to be developed for each truck to account for differences in mixer geometries and other characteristics. The results could also be influenced by the quantity of concrete in the truck and the density of the concrete.

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

*Advantages*:

- Concrete workability can be measured continuously while concrete is still in the mixer before discharge; and
- Unlike the delivery-chute meters, the devices that measure workability of concrete in the mixer do not require concrete to be discharged onto a delivery chute.

*Disadvantages*:

- The test devices described in the patent documents listed in Table 3.8 typically only measure one parameter and do not allow the calculation of yield stress and plastic viscosity;
- All of the devices need to be calibrated;
- Differences in mixer characteristics need to be considered in using any device; and
- The devices measure workability of an entire concrete sample and cannot detect variations in workability within a concrete sample.

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

The original version of the recording plastometer was based on the classical concept of a coaxial cylinders rheometer and featured an inner and outer cylinder. The outer cylinder of the recording plastometer was 305 mm (12 in.) in diameter and 203 mm (8 in.) in depth. The inner cylinder was 203 mm (8 in.) in diameter and 76 mm (3 in.) in depth, and was placed 102 mm (4 in.) above the bottom of the outer cylinder. The outer cylinder rotated while a spring-couple system attached to the inner cylinder measured the torque applied to the inner cylinder over time. Strain was defined as the relative displacement of the outer cylinder to the inner drum. The device could be operated at different speeds or an in oscillatory motion. It was not practical, however, to use the device to measure the torque on the inner cylinder at different shear rates, as most modern rheometers now do.

In a later, modified version of the device, shown in Fig. 3.26, the concrete was contained in a ring-shaped container while a stationary inner ring was inserted into the concrete. The torque required to keep the inner ring stationary was recorded as the ring container was measured.

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

*Advantage*:

- The recording plastometer represented one of the first attempts to use the concept of a coaxial cylinders rheometer to measure the rheology of concrete. Although it is no longer used, the plastometer served as a basis for the development of more sophisticated devices.

*Disadvantages*:

- The device did not enable the calculation of yield stress and plastic viscosity; and
- Slip occurred at the walls of the device.

**3.3.1.4.14** *Rheometer-4SCC*—The Rheometer-4SCC is a portable rheometer for SCC developed by Olafur H. Wallevik at the Icelandic Building Research Institute (IBRI) (Wallevik et al. 2006). It is capable of determining the yield stress and plastic viscosity of concrete mixtures with yield stresses ranging from 5 to 120 Pa, plastic viscosities ranging from 5 to 120 Pa·s, and maximum aggregate sizes of up to 22 mm (0.9 in.).

The Rheometer-4SCC, pictured in Fig. 3.27 and 3.28, consists of a control box and measurement unit that are connected when rheological tests are performed. The control box and measurement unit are each less than 25 kg (55 lb), which makes the device suitable for quality-control measurements at both building sites and in laboratories. To perform the test, concrete is placed in the sample bucket and the impeller, shown in Fig. 3.29, is inserted. The impeller is rotated at different rates, while the torque applied to the impeller is measured. The height of the impeller is 205 mm (8 in.), and the maximum width of the impeller from the rotational centerline is 90 mm (3.5 in.). The plastic viscosity and yield stress are calculated by fitting the torque and speed data to the Bingham model. The test procedure takes about 40 seconds.

*Fig. 3.27—BML viscometer (ConTec Viscometer 5) (left) and ConTec Rheometer-4SCC (right).*

*Fig. 3.28—ConTec Rheometer-4SCC at building site.*

The correlation between the Rheometer-4SCC and the BML Viscometer (ConTec Viscometer 5) was established during the development period, as shown in Fig. 3.30. The ability of the device to produce repeatable test results was also established at this time. The ConTec Viscometer 5 is a coaxial cylinder viscometer with defined shear area but the Rheometer-4SCC is a rotating impeller in medium. Further, the ConTec Viscometer 5 logs the torque through a very accurate load cell, but the Rheometer-4SCC estimates the torque by measuring the motor amperage. These two devices give very similar results, however, despite the simpler and handier construction of the latter.

*Advantages*:

- The device is lightweight and small in size, which makes it easy to use at construction sites;
- The operation of the device is automatic and the testing time is short; and
- The device measures torque and at various rotations speeds, which allows the calculation of plastic viscosity and yield stress.

*Disadvantages*:

- The device is relatively expensive compared with empirical test methods, although it is less expensive than many other available rheometers;

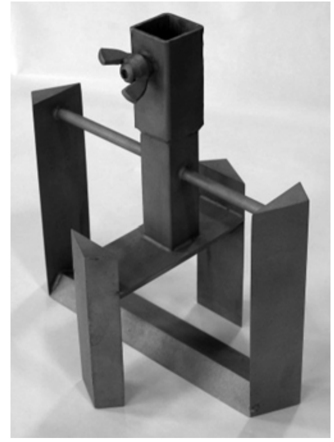


*Fig. 3.29—Impeller for Rheometer-4SCC.*

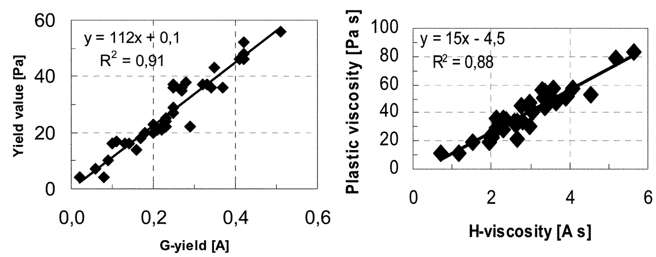



*Fig. 3.30—Correlation between BML viscometer (ConTec Viscometer 5) and Rheometer-4SCC (note that units of the Rheometer-4SCC's values, H-viscosity, and G-yield are arbitrary) (1000 Pa = 0.145 psi).*

- The results are not computed in fundamental units; and
- The device only measures SCC mixtures with aggregate sizes up to 22 mm (0.9 in.).

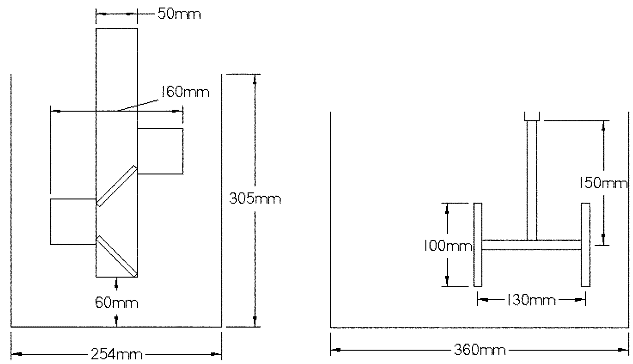
**3.3.1.4.15** *Soil direct shear test*—The direct shear test used for soil (Powers 1968) can be performed with fresh concrete to assess the cohesive strength of a concrete mixture. The results of the test are given in terms of soil mechanics parameters, not in terms of yield stress and plastic viscosity.

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

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

*Advantages*:

- The test essentially determines the yield stress of the concrete; and




Helical impeller (MH system) Offset H-impeller (LM system)

*Fig. 3.31—Impellers for Tattersall two-point test (Tattersall 1991) (1 mm = 0.039 in.).*

- The test provides additional information, namely the angle of internal friction, not available from most conventional tests.

*Disadvantages*:

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

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

The two-point device was originally developed by G. H. Tattersall at Sheffield University in the 1970s. Tattersall determined that coaxial cylinders rheometers would be inappropriate for measuring concrete because of the formation of a failure plane in the concrete between the cylinders. Instead, Tattersall decided to measure the torque required to turn an impeller in concrete. The development of the device began by using an ordinary food mixer fitted with a stirring hook and connected to a dynamometer wattmeter, which measured power needed to turn the hook. This initial device was referred to as the MK I. In contrast to a coaxial cylinders rheometer, the hook of the MK I constantly came in contact with undisturbed concrete (Tattersall and Banfill 1983). The calibration is performed using a Newtonian fluid of known viscosity and a power law fluid with a known flow curve, as described in Domone et al. (1999).

To extend the range of the initial food mixer device, a more sophisticated, specialized device was developed. This device, initially known as the MK II, is the device now commonly referred to as the Tattersall two-point device. The device consists of a stationary bowl mounted in a large frame. A hydraulic drive unit motor turns an impeller that is immersed in the concrete sample. Two different impellers are available for use based on the workability of the concrete. The MH system, which is used for slumps greater than 75 to 100 mm (3 to 4 in.), consists of four angled blades in a helical pattern on a central shaft. The blades provide mixing action by essentially lifting the concrete. Alternatively, the LM system is intended for lower-workability mixtures with slumps less than 50 mm (2 in.). It consists of an offset H-shaped blade that moves in a planetary motion in the concrete. When the H-shaped impeller is installed for use in a planetary motion, the device is sometimes referred to as the MK III. In addition to low-slump concretes, the LM system better measures SCC and certain high-performance concretes with high plastic viscosity because higher plastic viscosity reduces the efficiency of the mixing of the MH system. The MH and LM impeller systems are depicted in Fig. 3.31.

In early versions of the device, the speed of the impeller was manually controlled, and the torque was measured by monitoring the oil pressure in the hydraulic drive unit motor, as read from a pressure gauge. Later versions of the device use a tachometer and pressure transducer to allow continuous recording of data. The device has also been modified by adding a vibrator to characterize the effects of vibration on concrete rheology (Tattersall and Baker 1988).

The output of the device, shown in Eq. (3-10), is given in terms of $g$ and $h$ that are related to yield stress and plastic viscosity, respectively. The device needs to be calibrated to determine yield stress and plastic viscosity in fundamental units. The calibration is performed using a Newtonian fluid of known viscosity and a power law fluid with a known flow curve

$$T = g + hN \tag{3-10}$$

where $T$ = torque, and $N$ = rotation speed.

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

*Advantages*:

- The device measures torque at various rotation speeds, which allows the calculation of plastic viscosity and yield stress;
- The device has been used widely in research, particularly when compared with other rheometers;
- The choice of two impellers allows the measurement of a wide range of concrete mixtures, from 50 mm (2 in.) slump concrete up to SCC; and
- The device can be used to measure the effects of vibration on concrete rheology.

*Disadvantages*:

- The test device, in its current form, is larger and bulkier than other rheometers. The device's size limits its use in the field;
- The device must be calibrated to compute results in fundamental units; and

- Over long periods of time, the device can cause segregation in concrete mixtures, even when segregation would not be a problem in the field.

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

**3.3.1.5.1** *Intensive compaction test*—The intensive compaction test (Juvas 1990, 1994; Tattersall 1991; U.S. Patent and Trademark Office 1989, 1990) is a gyratory compactor used to measure the workability of concrete mixtures with slumps less than approximately 10 mm (1/2 in.). The test device—used for quality control, mixture proportioning, and research—has been standardized in Nordtest-Build 427 (Nordtest 1994).

The test apparatus is a machine that applies compression and shear forces to a concrete specimen while recording the density of the specimen. To perform the test, the concrete to be tested is placed in a cylindrical mold, which is loaded into the test apparatus. The mold is available in two diameters—a 100 mm (4 in.) diameter mold is used for concretes with maximum aggregate sizes of up to 20 mm (3/4 in.), while a 150 mm (6 in.) diameter mold is appropriate for maximum aggregate sizes up to 32 mm (1-1/4 in.). Two pistons at either end of the cylinder apply a compressive force to the sample. Simultaneously, the angle of inclination of the pistons rotates to apply a shearing motion to the concrete. This compaction technique is represented in Fig. 3.32. The pressure and speed of rotation can be adjusted for each test; however, these variables are held constant during each test. The volume of the sample, which is used to calculate density, is recorded continuously throughout the test. The test is performed in 3 to 5 minutes.

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

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

Although the larger 150 mm (6 in.) diameter model is too heavy and bulky for field use, the lightweight version of the 100 mm (4 in.) diameter model weighs approximately 55 kg (120 lb), and can be transported to a field site. Electricity and compressed air are required to perform the test.

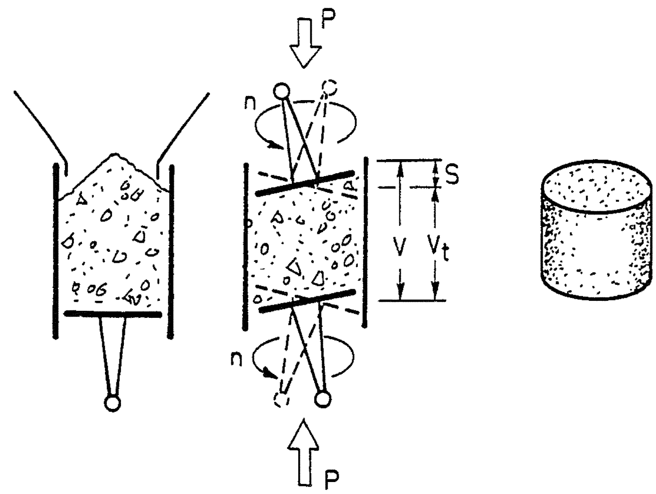



*Fig. 3.32—Compaction of concrete sample in intensive compaction factor device (U.S. Patent and Trademark Office 1989).*

*Advantages*:

- Research has shown that the test is capable of accurately measuring even small changes in mixture proportions;
- The test accurately simulates placement conditions for low-slump roller-compacted concretes;
- The test is fast and computer-controlled; and
- The test can be used for research, mixture proportioning, or quality control. The smaller 100 mm (4 in.) model is feasible for field use.

*Disadvantages*:

- The equipment is expensive, especially when compared with the Proctor test;
- The 150 mm (6 in.) diameter model is too heavy for field use; and
- The test does not incorporate vibration, which is commonly used in the placement of low-slump concrete and may be relevant to the evaluation of workability.

**3.3.1.5.2** *Kango hammer test*—The Kango hammer test (Juvas 1994; Bartos et al. 2002) attempts to measure workability by simulating the effect of vibration and pressing on low-slump concretes. The test is based on British standards BS 1924:1975 (British Standards Institute 1975a) and BS 1377:1975 (British Standards Institute 1975b). Concrete is placed in a cubic or cylindrical mold in two to three separate layers. A demolition hammer, which is mounted in a frame and equipped with a special bit that fits the shape of the mold, applies a constant pressure and vibration to each layer of concrete. After compaction of all layers, the density of the concrete specimen is determined. The greater the density of the compacted concrete specimen, the greater the compactability and workability of the concrete mixture.

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

*Advantages*:

- By using both vibration and pressure, the test accurately simulates field placement conditions; and

- The test is simple and easy to perform.

*Disadvantages*:

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

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

In its guidelines for developing mixture proportions for low-slump concretes, ACI 211.3R recommends using the proctor test.

*Advantages*:

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

*Disadvantages*:

The test does not incorporate vibration, which is commonly used to compact low-slump concretes; and

The test is time consuming; performing the test requires four to six samples to be prepared to fully define the unit weight versus moisture content curve.

**3.3.1.6** *Other test methods*—Several workability tests methods do not fit into the NIST classification scheme (Hackley and Ferraris 2001). Although these tests can provide useful information about the workability of concrete, they do incorporate the conventional approaches encompassed by the NIST classification scheme.

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

*Advantages*:

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

*Disadvantages*:

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

**3.3.1.6.2** *Soil triaxial test*—The soil triaxial test (Ritchie 1962; Powers 1968) can be used to measure the resistance of concrete to shear stress. The test is conducted with the same apparatus and with the same procedure as the triaxial test commonly used for soils. The results of the triaxial test are plotted on a Mohr diagram, which relates shear stress to normal stress. Based on the Mohr diagram, the Mohr envelope can be constructed to determine the maximum shear stress and corresponding normal stress at failure and the angle of internal friction. The test has been conducted on concrete mixtures with slumps ranging from 50 to 125 mm (2 to 5 in.).

*Advantages*:

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

*Disadvantages:*

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

**3.3.1.6.3** *System and method for controlling concrete production*—A system to monitor and control the quality of concrete throughout production based on rheological properties was patented (U.S. Patent and Trademark Office 2001). The system consists of multiple test devices that measure rheological properties of concrete at various stages of concrete mixture proportioning, production, transport, and placement. Each device is used appropriately; not all devices are used for a given concrete mixture. At a minimum, testing is conducted during the mixture proportioning process, at the concrete plant during concrete batching and mixing, and away from the concrete plant (either at the job site or during transit).

The first device described in the patent document consists of an inverted U-shaped box mounted within a rigid frame, as shown in Fig. 3.33. The entire device is submerged in a sample of fresh concrete. A piston moves up and down to force fresh concrete in and out of the box. The patent document suggests two methods to measure workability with this device: by determining the time required for the test device to produce a given deformation under a constant force, or by determining the resistance to shear at a given rate of deformation.

The second device is shown in Fig. 3.34. The U-shaped portion of the box is immersed in a sample of concrete. The rotation of the paddle forces concrete upward in the box and against stress sensors. A tachometer and ammeter measure the performance of the electric motor.

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

The fourth test device, which is applicable to pumped concretes, is essentially a venturi meter. The diameter of a pipe in a pumping system is narrowed. Pressure sensors monitor the changing stress states as the concrete moves through the narrowed section of the pipe.

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

*Advantages*:

- The system monitors the rheology of concrete throughout the production process; and
- Mixture proportions and later changes to mixture proportions can be made to optimize rheology and hardened concrete properties and to minimize costs.

*Disadvantages*:

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

**3.3.1.6.4** *Trowel test*—The trowel test (Bartos 1992; Washa 1998; Bartos et al. 2002) is a nonstandard test that subjectively characterizes the cohesiveness of a concrete mixture. As a sample of concrete is troweled, the cohesiveness of the mixture is judged by observing how well the concrete sticks together and whether the concrete sticks to the trowel. After the sample has been troweled, the magnitude of bleeding is observed subjectively. The test, when performed by an experienced operator, can determine whether a given concrete mixture has a sufficient amount of mortar. Harsh mixtures are difficult to trowel. The number of passes made by a trowel to bring the cement paste to the surface of the concrete can be used as an indication of workability. The test is most appropriate in situations when it is used in addition to other standard tests.

*Advantages*:

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

*Disadvantages*:

- The test is subjective, providing no numerical results;
- As a subjective test, the trowel test cannot be used in specifications; and
- While the test does simulate concrete finishing, it does not simulate other placement conditions.

**3.3.2** *Test methods for SCC*—SCC presents new challenges for the measurement of workability. Because SCC is capable of flowing readily under its own weight, its yield stress is

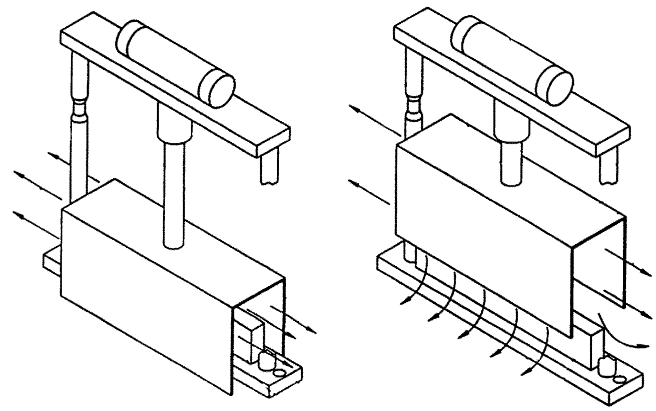


*Fig. 3.33—First test device in concrete production control system (U.S. Patent and Trademark Office 2001).*

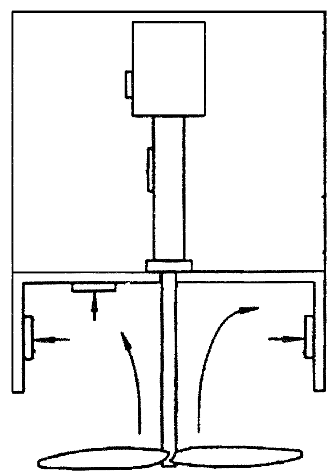


*Fig. 3.34—Second test device in concrete production control system (U.S. Patent and Trademark Office 2001).*

near zero. Although the yield stress of SCC is still evaluated, other properties related to plastic viscosity and segregation resistance should also be examined.

Workability tests for SCC can be broadly split into three categories: filling ability tests, passing ability tests, and segregation resistance tests. Each test described herein fits into one or more of these categories. In accordance with the NIST classification scheme, the tests for SCC typically fit into the confined flow and free-flow test categories. As previously discussed, many rotational rheometers are capable of measuring SCC. In addition to the test methods described herein, several other tests used for conventional concrete—such as the free orifice (Orimet) test, surface settlement test, and the settlement column segregation test—can be used for SCC.

**3.3.2.1** *Column-segregation test*—The column-segregation test (ASTM C1610/C1610M) measures the static segregation resistance of SCC. Similar tests have been presented by Rols et al. (1999), Lowke et al. (2003), and El-Chabib and Nehdi (2006). The column-segregation test differs from the settlement column-segregation test mainly in that the apparatus consists of a circular cross section, and no vibration is applied to the concrete.

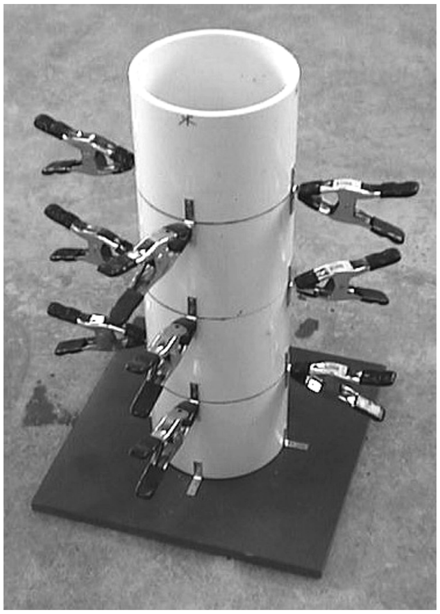


*Fig. 3.35—Column segregation test.*

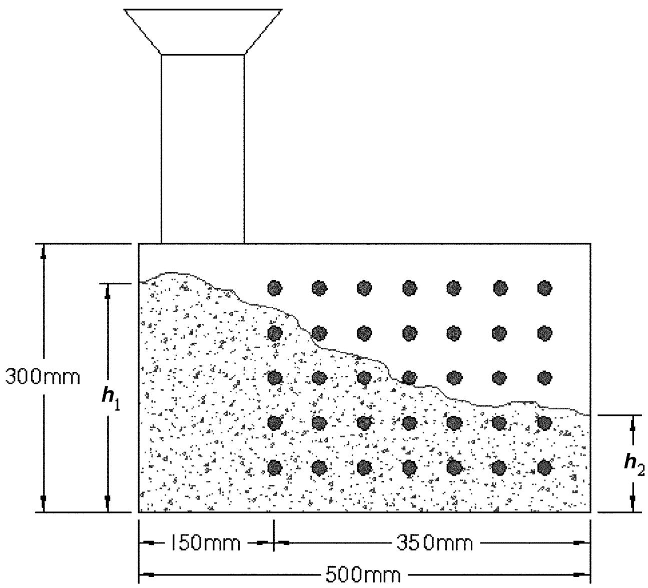



*Fig. 3.36—Simulated filling apparatus (1 mm = 0.039 in.).*

The test apparatus, which is shown in Fig. 3.35, consists of a 200 mm (8 in.) diameter, 660 mm (26 in.) tall PVC pipe split into three sections. The top and bottom sections are 165 mm (6.5 in.) in height, and the middle section is 330 mm (13 in.) high. Each section is clamped together to form a mortar-tight seal. Concrete is placed into the pipe and left undisturbed for 15 minutes. Each pipe section is then removed, and the concrete inside the top and bottom sections is collected. These two concrete samples are washed over a 4.75 mm (No. 4) sieve to retain all coarse aggregates, which are then dried to saturated surface-dry condition. The mass of aggregates retained in the top ($M_{top}$) and bottom ($M_{bottom}$) pipe sections are measured and used to compute percent static segregation, as shown in Eq. (3-11)

$$\text{percent static segregation} = \left\{ \begin{array}{ll} \dfrac{M_{bottom} - M_{top}}{M_{bottom} + M_{top}} \times 100\% & \text{if } M_{bottom} > M_{top} \\ 0\% & \text{if } M_{bottom} < M_{top} \end{array} \right\} \qquad (3\text{-}11)$$

**3.3.2.2** *Fill box test (simulated filling test, filling capacity box, Kajima test)*—The fill box test (Yurugi et al. 1993) measures the filling ability, passing ability, and segregation resistance of SCC. The apparatus consists of a clear plastic box with 35 plastic 20 mm (3/4 in.) diameter bars (smooth tubes), as shown in Fig. 3.36. An early version of the test featured a wedge-shaped box instead of a rectangular box, and did not include a funnel. Concrete is poured at a constant rate into the funnel and allowed to flow into the box until the height of the concrete reaches the height of the top row of bars. After the concrete comes to rest, the height of the concrete at the two ends of the box is measured.

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

$$\text{filling capacity} = \frac{(h_1 + h_2)}{2h_1} \cdot 100\% \qquad (3\text{-}12)$$

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

The test is a good representation of actual placement conditions of highly congested sections; however, the test is bulky and difficult to perform on site.

**3.3.2.3** *J-ring test*—The J-ring test is used to characterize the passing ability of SCC (ASTM C1621). The J-ring test device can be used along with the slump flow test, the Orimet test, or the V-funnel test to evaluate multiple characteristics of SCC (Sonebi and Bartos 1999; Sonebi et al. 2001; EFNARC 2005; Bartos et al. 2002; Sonebi and Bartos 2002, 2003). The J-ring, as shown in Fig. 3.37, is a rectangular section open steel ring with a 300 mm (12 in.) diameter. Vertical holes drilled in the ring allow standard reinforcing bars to be attached to the ring. Each reinforcing bar extends 100 mm (4 in.) from the ring. The spacing of the bars may be adjustable, although three times the maximum aggregate size is typically recommended.

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

Various interpretations of the test results have been suggested. The measures of passing ability and filling ability are not independent. To characterize filling ability and passing ability, the horizontal spread of the concrete sample

**Table 3.9—Precision of J-ring flow spread and J-ring flow time $T_{50J}$**

| | J-ring flow spread, mm (in.) | | | J-ring flow time $T_{50J}$, seconds | | | J-ring height (height difference), mm (in.) | |
|---|---|---|---|---|---|---|---|---|
| | <600 (23.6) | 600 to 750 (23.6 to 29.5) | >750 (29.5) | <3.5 | 3.5 to 6 | >6 | <20 (0.8) | >20 (0.8) |
| Repeatability $r$ | 59 (2.3) | 46 (1.8) | 25 (1.0) | 0.70 | 1.23 | 4.35 | 4.6 (0.18) | 7.8 (0.31) |
| Reproducibility $R$ | 67 (2.6) | 46 (1.8) | 31 (1.2) | 0.90 | 1.32 | 4.34 | 4.9 (0.19) | 7.8 (0.31) |

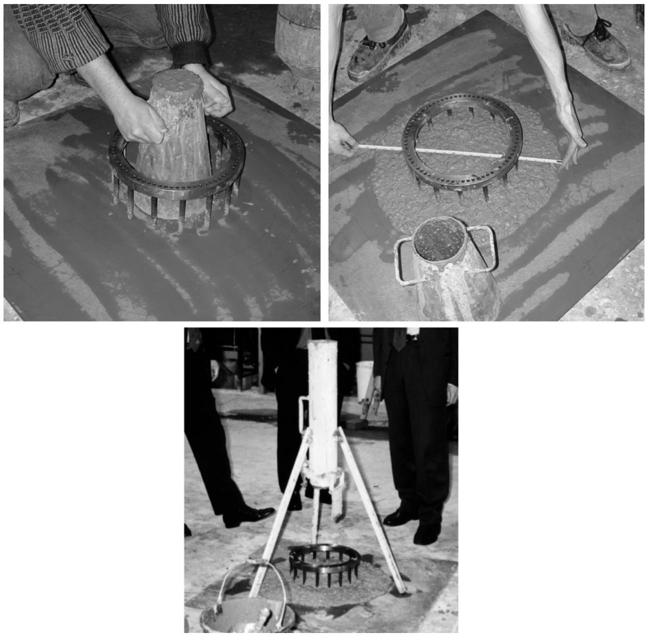


*Fig. 3.37—J-ring test apparatus with slump cone (top) and Orimet device (bottom).*

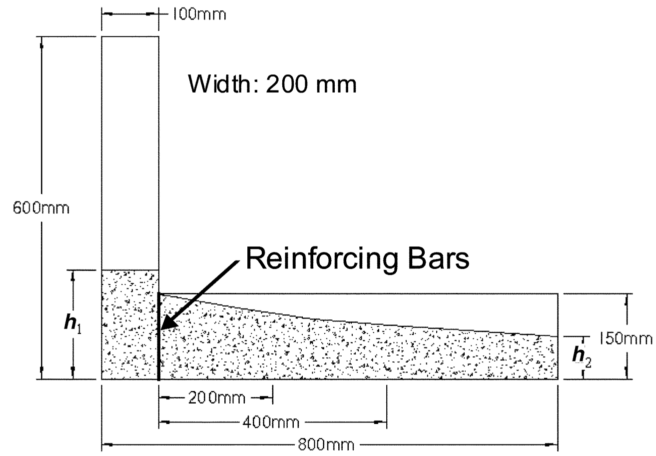



*Fig. 3.38—L-box test apparatus (1 mm = 0.039 in.).*

is measured after the concrete passes through the gaps in the bars of the J-ring and comes to rest. Also, the difference in height of the concrete just inside the bars and just outside the bars is measured at four locations. The smaller the difference in heights, the greater the passing ability of the concrete. Alternatively, the horizontal spread with and without the J-ring can be compared as a measure of passing ability.

Based on interlaboratory testing 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 J-ring flow spread and J-ring flow time $T_{50J}$ are given in Table 3.9.

**3.3.2.4** *L-box test*—The L-box test (Petersson et. al. 1996) measures the filling ability and passing ability of SCC. Originally developed in Japan for underwater concrete, the test is also applicable for highly flowable concrete.

As the test name implies, the apparatus consists of an L-shaped box, shown in Fig 3.38. Concrete is initially placed in the vertical portion of the box, which measures 600 mm (23.6 in.) in height and 100 x 200 mm (3.9 x 7.9 in.) in section. A door between the vertical or horizontal portions of the box is opened and the concrete is allowed to flow through a line of vertical reinforcing bars and into the 700 mm (27.6 in.) long, 200 mm (7.9 in.) wide, and 150 mm (5.9 in.) tall horizontal portion of the box. In the most common arrangement of reinforcing bars, three 12 mm (1/2 in.) bars are spaced with a clear spacing of 35 mm (1.4 in.). Generally, the spacing of the reinforcing bars should be three times the maximum aggregate size. Various dimensions for the L-box have been used, and no one set of dimensions is considered official; however, the dimensions described previously seem to be the most common.

The time for concrete to reach points 200 or 400 mm (7.9 or 15.7 in.) ($T_{20}$ or $T_{40}$) down the horizontal portion of the box is recorded. After the concrete comes to rest in the apparatus, the heights of the concrete at the end of the horizontal portion, $h_2$, and in the vertical section, $h_1$, are measured. The block ratio is computed as the ratio of $h_2$ to $h_1$. If the concrete being tested is truly self-leveling, the value of the blocking ratio will be 1. Segregation resistance can be evaluated visually. A concrete sample with coarse-aggregate particles that reach the far end of the horizontal part of the box exhibits good resistance to segregation. The L-box can be disassembled after the concrete has hardened. By cutting out samples of the hardened concrete, additional information about the concrete's resistance to segregation can be determined, as shown by Tanaka et al. (1993).

Based on interlaboratory testing with two replicates and 22 operators from 11 laboratories from the European project Testing SCC (2005), the repeatability $r$ and the reproducibility $R$ according to ISO 5725 (International Organization for Standardization 1994) for different values L-box blocking ratio are given in Table 3.10.

**3.3.2.5** *Penetration test for segregation*—The penetration test for segregation (Bui et al. 2002a,b; Bartos et al. 2002) measures the penetration resistance of highly fluid concrete and SCC.

The test apparatus, shown in Fig. 3.39, consists of a hollow cylindrical penetration head that is allowed to sink under its own weight into a sample of concrete. The penetration head has an inside diameter of 75 mm (3 in.), a thickness of 1 mm (0.04 in.), and a height of 50 mm (2 in.). A rod attached to

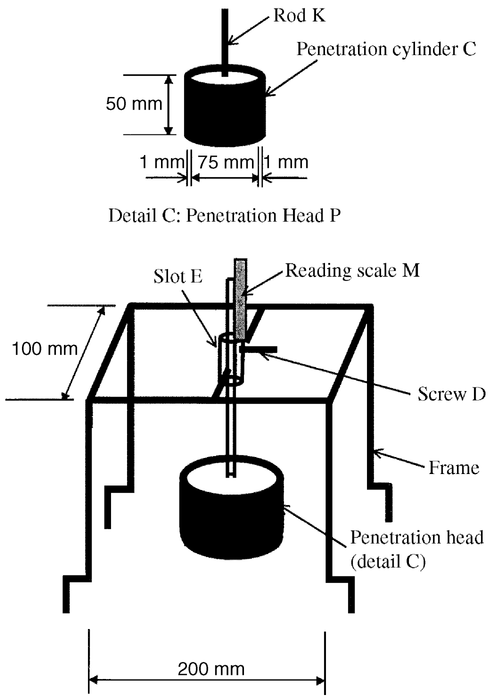



*Fig. 3.39—Penetration apparatus (1 mm = 0.039 in.).*

the penetration head slides through a frame, which includes a graduated scale for measuring penetration depth. Several different dimensions for the concrete container have been used by different researchers. Bui et al. (2002a) set the apparatus on top of an L-box with cross-sectional dimensions of 200 x 200 mm (7.8 x 7.8 in.) (instead of the more commonly used dimensions of 100 x 200 mm [3.9 x 7.8 in.]). The container should be placed on level ground, and should not be moved during the test. The concrete, which is not consolidated with vibration or tamping, is allowed to sit for 2 minutes after being placed into the container. The cylinder is then placed on top of the concrete surface and the depth of penetration is measured after 45 seconds. This measurement is performed at a total of three different locations on the concrete surface. When the concrete mixture is susceptible to segregation, the coarse aggregate particles will settle from the top surface of the concrete, and the penetration depth will increase. If the average depth of penetration is greater than 8 mm (0.3 in.), the concrete is considered to have poor segregation resistance. Alternatively, from the Testing SCC (2005) project, the proposed criteria for the penetration test are:

- Concrete has good segregation resistance if the penetration is smaller than 20 mm (0.8 in); and
- Concrete has poor segregation resistance if the penetration is higher than 20 mm (0.8 in.).

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

Based on interlaboratory testing with two replicates and 20 operators from 10 laboratories from the European project Testing SCC (2005), the repeatability *r* and the reproducibility *R* according to ISO 5725 (International Organization for Standardization 1994) for different values of the penetration depth are given in Table 3.11.

**Table 3.10—Precision of L-box blocking ratio $h_2/h_1$**

| Blocking ratio | 1 | 0.9 | 0.8 | 0.7 | <0.65 |
|---|---|---|---|---|---|
| Repeatability *r* | 0.01 | 0.06 | 0.10 | 0.15 | 0.18 |
| Reproducibility *R* | 0.03 | 0.07 | 0.11 | 0.16 | 0.18 |

**Table 3.11—Precision of penetration depth**

| Penetration depth, mm (in.) | 5 (0.2) | 10 (0.4) | 15 (0.7) | >17 (0.7) |
|---|---|---|---|---|
| Repeatability *r*, mm (in.) | 5 (0.2) | 8 (0.3) | 11 (0.4) | 12 (0.5) |
| Reproducibility *R*, mm (in.) | 5 (0.2) | 8 (0.3) | 11 (0.4) | 12 (0.5) |

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

**3.3.2.7** *Slump flow test*—The simplest and most widely used test method for SCC is the slump flow test (ASTM C1611). The test was originally used to measure the consistency of underwater concrete, and has also been used to measure highly flowable concrete.

To perform the test, a conventional slump cone is placed on a rigid, nonabsorbent plate and filled with concrete without tamping. The plate should be placed on a firm, level surface. The slump cone is lifted and the horizontal spread of the concrete is measured. In a variation on this test method, the slump cone can be filled in the inverted position. For an additional measure of flowability, the time required for the concrete to spread to a diameter of 500 mm (19.7 in.) can be measured ($T_{50}$).

It is possible to qualitatively assess the stability of concrete after performing the slump flow test. A visual stability index (VSI) has been developed as a means of determining stability as shown Table 3.12 (Daczko and Kurtz 2001). A numerical score, on a scale of 0 to 3, is assigned based on a visual evaluation of the segregation and bleeding in the concrete sample. Typically, SCC with a rating of 0 or 1 could be considered acceptable.

Based on interlaboratory testing with two replicates and 20 operators from 10 laboratories (Testing SCC 2005), the repeatability *r* and the reproducibility *R*, according to ISO 5725 (International Organization for Standardization 1994) for different values of slump flow spread and slump flow time $T_{50}$, are given in Table 3.13.

**3.3.2.8** *U-box test*—The U-box test (Kuriowa et al. 1993) measures filling ability and is similar to the L-box test. The U-box test was developed in Japan, and is sometimes referred to as the box-shaped test. Like other workability tests for SCC, the U-box test is also applicable to highly flowable concrete and underwater concrete.

### Table 3.12—Visual stability index ratings (ASTM C1611)

| VSI value | Criteria |
|---|---|
| 0 = highly stable | No evidence of segregation or bleeding. |
| 1 = stable | No evidence of segregation and slight bleeding observed as a sheen on the concrete mass. |
| 2 = unstable | A slight mortar halo ≤ 0.5 in. (10 mm) or aggregate pile in the center of the concrete mass, or both. |
| 3 = highly unstable | Clearly segregating by evidence off a larger mortar halo >0.5 in. (10 mm), or a large aggregate pile in the center of the concrete mass, or both. |

### Table 3.13—Precision slump flow spread and flow time $T_{50}$

| | Slump flow spread, mm (in.) | | | Slump flow time $T_{50}$, seconds | | |
|---|---|---|---|---|---|---|
| | <600 (23.6) | 600 to 750 (23.6 to 29.5) | >750 (29.5) | <3.5 | 3.5 to 6 | >6 |
| Repeatability *r* | N/A | 42 (1.7) | 22 (0.9) | 0.66 | 1.18 | N/A |
| Reproducibility *R* | N/A | 43 (1.7) | 28 (1.1) | 0.88 | 1.18 | N/A |

The apparatus consists of a U-shaped box, as shown in Fig. 3.40. Concrete is placed in the left side of the box. An alternative version of the apparatus features a flat bottom instead of a curved bottom. Ideally, the box should be made of clear plastic to permit the observation of the concrete in the box. To start the test, the door dividing the two halves of the box is opened, and concrete is allowed to flow from the left half of the box into the right half. Reinforcing bars are placed at the location of the door. Although the spacing of the bars is adjustable, the most common arrangement is 13 mm (1/2 in.) diameter bars with a clear spacing of 35 mm (1.4 in.). The time from the opening of the door until the concrete ceases to flow is recorded. The height of the concrete in each side of the box is measured. Concrete with good filling ability should reach a height of at least 250 mm (9.8 in.) on the right side of the box. In some versions of the test, a surcharge load is applied to the concrete on the left side of the box. This surcharge load is unnecessary for SCC, and is generally not used.

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

**3.3.2.9** *V-funnel test*—The V-funnel test (Ozawa et al. 1995) is used to measure the filling ability of SCC, and can also be used to judge segregation resistance. The test method is similar to the concept of the flow cone test used for highly fluid grout.

The test apparatus, shown in Fig. 3.41, consists of a V-shaped funnel with a height of 425 mm (16.7 in.), a top width of 490 mm (19.3 in.), a bottom width of 65 mm (2.6 in.), and a thickness of 75 mm (3.0 in.). At the bottom of the V-shape, a rectangular section extends downward 150 mm (5.9 in.). Alternatively, an O-shaped funnel with circular cross section can be used. The entire funnel is filled with concrete without tamping or vibration. The door at the bottom of the funnel is opened, and concrete is allowed to flow out of the funnel and into a bucket. The flow time for all of the concrete to exit the funnel is recorded as a measure of the filling ability. For SCC, the flow time should be less than 10 seconds. To measure segregation resistance, the V-funnel is refilled with concrete and allowed to sit for a given period of time, typically 5 minutes. The door is again opened, and the flow time is recorded. An increase in flow time after the concrete has remained at rest may indicate poor segregation resistance; however, thixotropy can also increase the flow time after rest. Further, nonuniform flow of concrete from the funnel suggests poor segregation resistance.

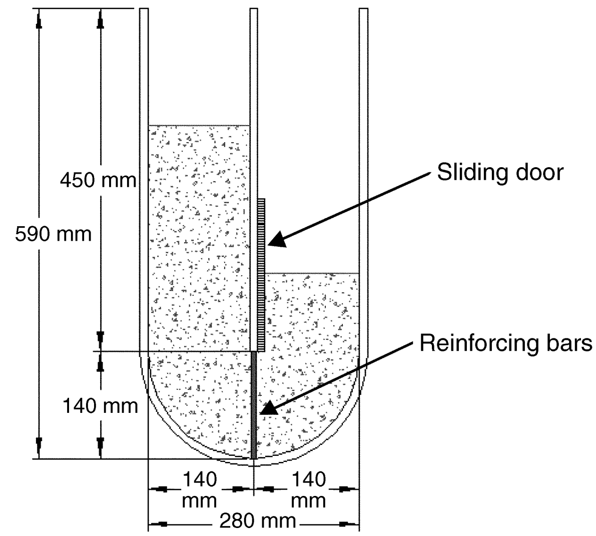



*Fig. 3.40—U-box test apparatus (1 mm = 0.039 in.).*

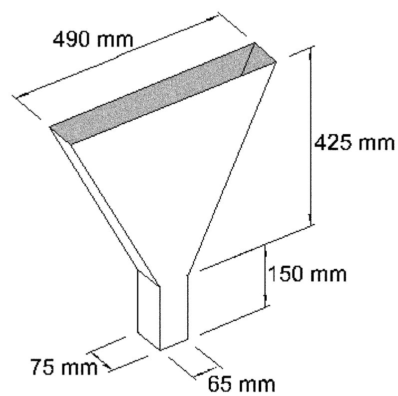



*Fig. 3.41—V-funnel test apparatus (1 mm = 0.039 in.).*

The average flow-through speed $V_m$ is calculated in terms of the flow-through time $t_0$

$$V_m = \frac{0.01}{(0.065 \times 0.075) \times t_0} = \frac{2.05}{t_0}(\text{m/s}) \qquad (3\text{-}13)$$

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

$$S_f = \frac{t_5 - t_0}{t_0} \qquad (3\text{-}14)$$

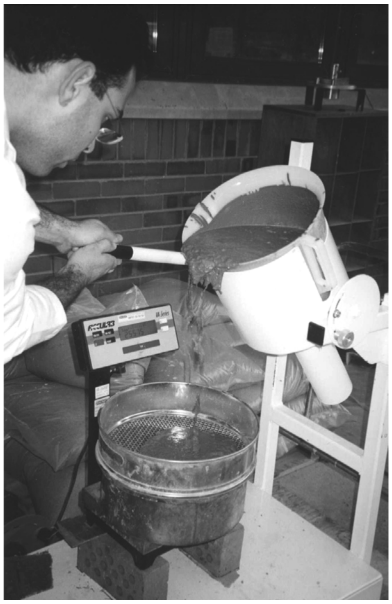


*Fig. 3.42—Wet sieving stability test apparatus.*

Based on interlaboratory testing with two replicates and 16 operators from eight laboratories (Testing SCC 2005), the repeatability $r$ and the reproducibility $R$ according to ISO 5725 (International Organization for Standardization 1994) for different values of V-funnel flow time are given in Table 3.14.

**3.3.2.10** *Wet sieving stability test (GTM screen stability test)*—The wet sieving stability test was developed by a French contractor to measure the segregation resistance of SCC.

To perform the test, a 10 L (0.35 ft$^3$) sample of concrete is placed inside a bucket and allowed to sit for 15 minutes to allow any segregation to occur. The container is sealed to prevent evaporation. After sitting for 15 minutes, approximately the top 2 L (0.07 ft$^3$) of the concrete is poured from the bucket from a height of 500 mm (19.7 in.) onto a 5 mm (0.20 in.) sieve, as shown in Fig. 3.42. Mortar from the sample is allowed to flow through the sieve into a lower sieve pan for a period of 2 minutes. The mass of the concrete poured onto the sieve, $M_a$, and the mass of mortar in the sieve pan, $M_b$, are measured and used to calculate the segregation ratio

$$\text{segregation ratio} = \frac{M_b}{M_a} \cdot 100\% \qquad (3\text{-}15)$$

The segregation ratio should be between 5 and 15% for acceptable segregation resistance. Concrete with a segregation ratio above 15% will exhibit too much segregation. If the segregation ratio is less than 5%, the sample may be too cohesive (Bartos et al. 2002). From the Testing SCC (2005) project, the proposed criteria for the sieve stability test are:

- Concrete has good segregation resistance if the sieved portion value is lower than 20; and
- Concrete has poor segregation resistance if the sieved portion value is higher than 20.

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

**Table 3.14—Precision of V-funnel flow time**

| | V-funnel flow time, seconds | | | | |
|---|---|---|---|---|---|
| | 3 | 5 | 8 | 12 | >15 |
| Repeatability $r$, seconds | 0.4 | 1.1 | 2.1 | 3.4 | 4.4 |
| Reproducibility $R$, seconds | 0.6 | 1.6 | 3.1 | 5.1 | 6.6 |

**Table 3.15—Precision of sieved portions**

| | Sieved portion, % | |
|---|---|---|
| | <20 | >20 |
| Repeatability $r$, % | 3.7 | 10.9 |
| Reproducibility $R$, % | 3.7 | 10.9 |

Based on interlaboratory testing with two replicates and 20 operators from 10 laboratories from the European project Testing SCC (2005), the repeatability $r$ and the reproducibility $R$ according to ISO 5725 (International Organization for Standardization 1994) for different values of sieved portions are given in Table 3.15.

**3.3.3** *Workability tests for pastes and grouts*—Test devices with varying degrees of complexity are available to measure the rheology of cement pastes and grouts. These devices typically use similar principles as devices used to measure concrete, but usually feature smaller dimensions. Some devices, such as the flow-trough test (Section 3.3.3.8), are used for both concrete and grouts. Furthermore, many concrete rheometers have smaller versions available for measuring mortar.

The rheology of cement paste is often measured in the laboratory. Because, in many cases, cement paste can be measured more easily and accurately than concrete, the results of cement paste testing are more significant. Changes in cement paste rheology can be correlated to concrete rheology.

**3.3.3.1** *Flow cone and marsh cone tests*—Several versions of a funnel test are used to measure the workability of pastes and grouts. These devices differ in dimensions and intended use; however, they all work on the same principle of measuring the elapsed time for fresh paste or grout to flow through the opening of a funnel.

The flow cone test (Scanlon 1994) is used for measuring the flow properties of grout for preplaced-aggregate concrete, but can also be used for other highly flowable grouts. The test is standardized in ASTM C939, and is considered appropriate for use in both the field and the lab. To perform the test, grout is poured into the flow cone, which is shown in Fig. 3.43. The level indicator ensures that a standard volume of grout is used for each test. The opening at the bottom of the cone is opened, and the time for the grout to flow out of the cone is recorded. ASTM procedure is intended for grouts with flow times less than 35 seconds. The test is not considered applicable to grouts that become clogged in the cone and do not continuously flow out the opening. Test results for such mixtures should be discarded. According to ASTM C939, the single laboratory standard deviation is 0.88 seconds.

The Marsh cone test (Zhor and Bremner 1998; Ferraris et al. 2001) is a nonstandard test most typically used for oil-well cements. The Marsh cone is a funnel with a long neck and an opening of 5 mm (0.20 in.). A stand holds the Marsh cone in place above a glass graduated cylinder. After 1 L (0.04 $ft^3$) of cement paste is placed in the cone, the orifice at the bottom of the neck is opened. The time for various volumes of paste to flow out of the orifice is measured. Because the weight of the cement paste in the funnel should be sufficient to overcome the yield stress, the time of flow should be related to viscosity. Ferraris et al. (2001), however, showed that the flow time from the Marsh cone test was not correlated to the viscosity measured with a laboratory parallel plate rheometer and hypothesized that the lack of correlation was related to factors such as friction and sedimentation in the Marsh cone.

Mortsell et al. (1996) developed the FlowCyl, which is a modification of the Marsh cone. In the FlowCyl, an electronic ruler and data logger are used to measure the flow rate versus fluid height in the Marsh cone. This relationship is compared with that of an ideal fluid to compute the flow resistance ratio, which is a measure of flow properties.

**3.3.3.2** *Lombardi plate (plate cohesion meter)*—The Lombardi plate cohesion meter can be used to measure the cohesiveness of the grout (Lombardi 1985; Svermova et al. 2003). The apparatus consists of an electronic scale and a thin steel plate—100 x 100 x 1 mm (3.9 x 3.9 x 0.04 in.)—on which the grout can stick. The clean, dry plate is weighed and then submerged once into the grout. The plate is then withdrawn and weighed again after any dropping of grout has stopped (Fig. 3.44).

There was an estimated error at 95% confidence limit of 0.08 mm (0.003 in.) for grout having a mini-slump flow of 117 mm (4.6 in.), and a good relationship between mini-slump and the plate cohesion meter was obtained (Svermova et al. 2003).

**3.3.3.3** *Mini-flow test*—The mini-flow test (Zhor and Bremner 1998) is a variation of the mini-slump test described in the previous subsection. The Plexiglas sheet used in the modified version of the mini-slump test is mounted to a standard flow table, as described in ASTM C230/C230M. After the mini-slump cone is lifted from the sample of cement paste, the table is dropped 15 times in 15 seconds. The rest of the test procedure is unchanged. The mass of the cement paste is measured to determine air content. The results of the mini-flow test reflect the addition of energy to the cement paste. The mini-flow test is more appropriate than the mini-slump test for stiff mixtures.

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

The mini-slump cone, as shown in Fig. 3.45, is simply a small version of the slump cone for concrete (ASTM C143/C143M). The mini-slump cone has a bottom diameter of 38 mm (1.5 in.), a top diameter of 19 mm (0.75 in.), and a height of 57 mm (2.25 in.) (Fig. 3.45). The cone is placed in the center of a square piece of glass on which the diagonals and medians are traced. The cone is lifted, and after 1 minute, the average spread of the paste, as measured along the two diagonals and two medians, is recorded.

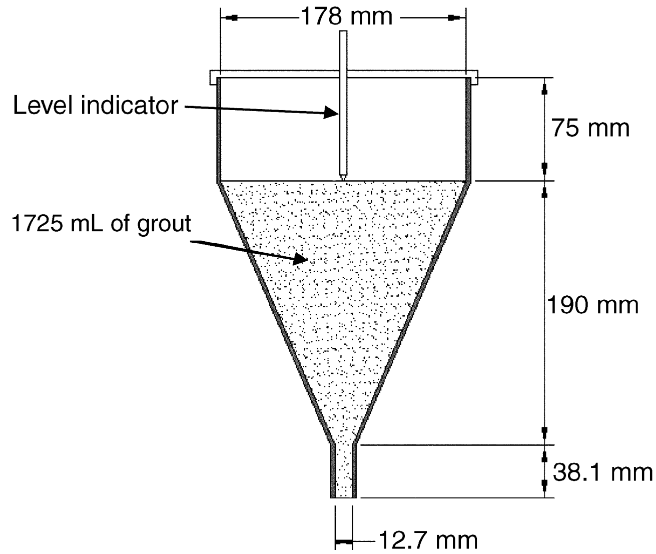


*Fig. 3.43—Cross section of flow cone (1 mm = 0.039 in.; 1 mL = 0.061 $in.^3$).*


*Fig. 3.44—Lombardi plate (plate cohesion meter apparatus).*

Zhor and Bremner (1998) modified the device to measure the air-entraining and plasticizing effects of admixtures on cement pastes. A clear Plexiglas sheet, which is used instead of glass, is set on a balance. After the cone is removed, the concrete's mass is measured and used to determine the air content of the paste in accordance with ASTM C185. The paste is left to harden on the Plexiglas for 2 days. A planimeter is then used to measure the area of the hardened paste on the Plexiglas sheet.

Like the conventional slump test, the results of the mini-slump test should be related to yield stress. Research conducted by Ferraris et al. (2001) into the influence of mineral admixtures on the rheology of cement paste showed poor correlation between the results of the mini-slump test and yield stress, as measured with a laboratory-grade parallel plate rheometer. Svermova et al. (2003) carried out a statistical experimental program on grouts containing limestone

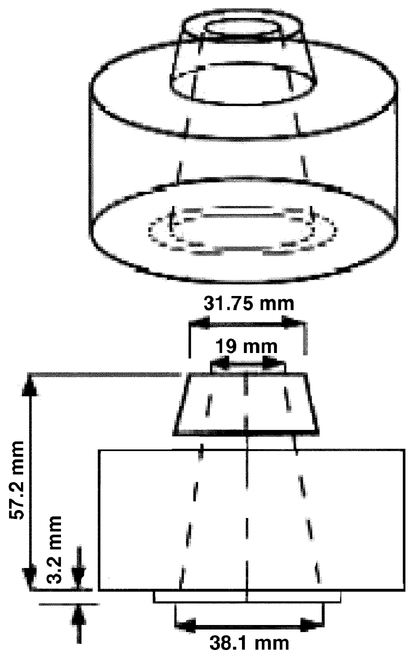



*Fig. 3.45—Mini-slump flow of grout (1 mm = 0.039 in.).*

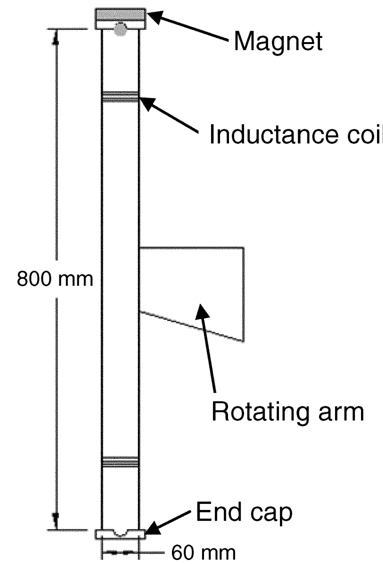



*Fig. 3.46—Turning tube viscometer (1 mm = 0.039 in.).*

powder, and the results showed a good relationship between the mini-slump flow and plastic viscosity ($R^2$ = 0.75); however, the correlation between mini-slump flow and yield stress was poor ($R^2$ = 0.57).

**3.3.3.5** *Turning tube viscometer*—The turning tube viscometer (Hopkins and Cabrera 1985; Ferraris 1999) is based on the same principle as the moving sphere viscometer—namely, Stokes' Law—but is only considered appropriate for testing mortar (Fig. 3.46).

An 800 mm (31.5 in.) long, 60 mm (2.4 in.) diameter tube is attached to a rotating arm, which allows the tube to be rotated in the vertical plane. A metal ball is allowed to fall through the fresh mortar in the tube. A magnet can be placed on the specially milled end caps to ensure that the ball starts in the center of the tube. Inductance coils wrapped around the tube at two locations detect when the ball passes to determine the time for the ball to fall a known distance.

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

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

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

The Vicat needle apparatus consists of a 300 g (10.6 oz) moveable rod with a 1 mm (0.04 in.) diameter needle at one end. The rod slides through a frame, where an indicator on the rod moves over a scale mounted to the frame. A specimen of fresh cement paste prepared in a certain prescribed manner is placed in a conical ring below the frame. After 30 minutes, the needle is placed on the cement paste specimen and allowed to settle under its own weight. The depth of penetration is recorded from the scale. The test is repeated every 15 minutes (10 minutes for Type III cement) until a penetration depth of less than 25 mm (1 in.) is obtained. Each subsequent reading is taken at a different location on the paste specimen.

Similarly, the penetration test method described in ASTM C403/C403M is used to determine the setting time of concrete by measuring the penetration resistance of mortar specimens sieved from concrete samples. Unlike the Vicat needle test, the apparatus used in ASTM C403/C403M measures the force required to cause penetration, not the depth of penetration.

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

The device, which is depicted in Fig. 3.47, consists of a metal cylinder mounted on a rotating turntable. A paddle inserted in the cylinder is connected to a calibrated spring that measures the torque on the paddle. As the cylinder is rotated, the mortar applies a torque to the paddle. Traditionally, the device was operated at only one rotation speed. Banfill (1990) modified the device to measure torque at multiple rotation speeds. To obtain a plot of torque versus speed, the speed of the cylinder is changed in steps from zero to a maximum speed and back to zero. The device can be calibrated to correlate values for torque and speed to yield stress and plastic viscosity.

The ViscoCorder works well for fluid mortars; however, stiff mortars slip on the wall of the container, resulting in torque readings that are not an accurate representation of rheology. The container does not include any protrusions to prevent slip. Banfill (1990) recommends that the device be automated to change rotation speed and continuously record torque versus time.

**3.3.3.8** *Wuerpel device*—The Wuerpel device (Maultzsch 1990) measures the consistency of mortars by applying a shear force to a mortar specimen and measuring deformation energy (Fig. 3.48).

The apparatus consists of a quadratic mold with side lengths of 100 mm (3.9 in.) and a height of 50 mm (2.0 in.). The corners of the mold are hinged to allow the mold, which is filled with compacted mortar, to deform from a square shape to a rhombus shape. The operation of the device is depicted conceptually in Fig. 3.48. A load cell and a displacement transducer continuously measure the deformation force and the displacement of the mold, respectively. The area under the resulting force-displacement curve represents the deformation energy, which is used to characterize workability.

The test method was developed in Germany and was briefly included in German standards in the late 1960s. Maultzsch (1990) used the test to measure the change in workability with time for mortars with a maximum aggregate size of 4 mm (0.16 in.) and found that the test device works particularly well for stiff mortars, although it is applicable to a wide range of workability. The results of the test are dependant on the deformation speed of the device.

## 3.4—Criteria for evaluating test methods

Based on the advantages and disadvantages of the existing workability test methods described in Section 3.3, criteria for the creation and evaluation of workability test methods can be developed. Any test method to be used in the field should measure workability in a more comprehensive way than the slump test and be competitive with the slump test in terms of cost-benefit, speed, and the value of the results. The workability requirements should be well defined. The criteria for evaluating a workability field test method are described as follows:

- *Parameters measured*—Any new test method should measure dynamic properties of moderate- and low-workability concretes, and should appropriately measure concrete that exhibits high thixotropy. To accomplish this, the test should add energy to the concrete, such as with vibration. The energy added should be compared with the one experienced by the concrete during placement. For SCC, there is no added energy; thus, the measured properties using vibration will be not be reflective of the properties exhibited by the concrete during placement. The test should directly or indirectly measure yield stress and plastic viscosity.
- *Ruggedness*—Any new test device should be sufficiently rugged to be used regularly on a job site. Depending on the accuracy of the device, it may also be used in the lab for research and mixture proportioning.

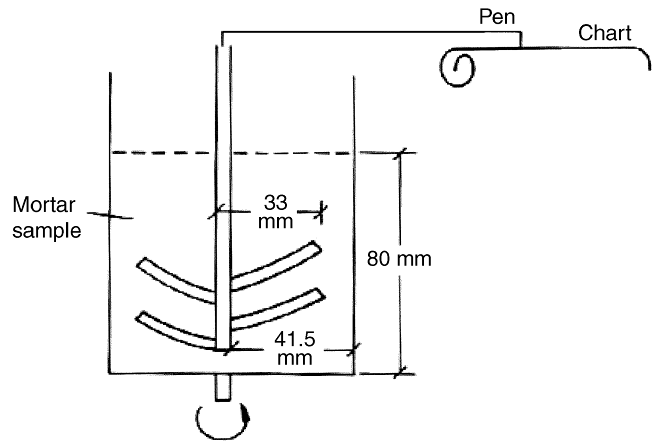



*Fig. 3.47—ViscoCorder (Banfill 1990) (1 mm = 0.039 in.).*

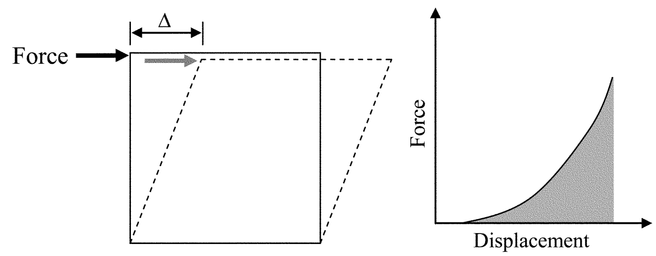



*Fig. 3.48—Operation of Wuerpel device.*

- *Workability range*—Any new test method should measure the widest possible range of workability. The wider the range of workability, the more versatile the device will be, and the greater the chance that the device will be adopted widely. In reality, no device can measure all concrete, from zero-slump to SCC.
- *Aggregate size restrictions*—The device should feature proper geometry to allow testing of concrete with a wide range of aggregate sizes. Based on existing tests, such as the slump test, the device should measure concrete with a maximum aggregate size of up to 40 mm (1.5 in.).
- *Cost*—The cost of any device, when mass produced, should be competitive with simple, currently available devices, most notably the slump test. Therefore, devices higher in cost than the slump test should provide sufficiently improved information to justify the higher cost.
- *Sample size*—The sample size should be kept to a minimum; however, the sample size should be sufficiently large to be representative of the concrete and to enable accurate determination of rheological parameters.
- *Test speed*—The speed with which the test can be conducted should be minimized. The slump test can be performed in several minutes. Other tests allow workability to be monitored continuously with little interruption of construction operations.
- *Complexity/training*—Any new test device should be sufficiently simple to be performed and interpreted by field workers. Although the test may report results in terms of yield stress and plastic viscosity, field personnel not familiar with concrete rheology should be able to interpret these values and make quick decisions.

The use of nomographs or an embedded electronic device can facilitate the interpretation of results in the field.

- *Data processing*—The results of the test should be obtained directly without any calculations or processing. When data processing is required, an embedded electronic device should perform all calculations and display simple results that can be used directly.
- *Size and weight*—The device should be small and light so that one person can easily move it around the job site.
- *Number of people required to perform test*—One person should be able to quickly perform the test method and be able to perform other duties on the job site, instead of only monitoring workability.
- *Electricity*—Although any new test device should be able to operate without electricity, devices requiring power should not be eliminated. Many construction sites have power readily available. Alternatively, batteries can be used.

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

While no test method will likely incorporate all of the criteria enumerated previously, a device that meets the majority of these criteria stands the greatest chance of being adopted by all parties in the concrete industry. No test will be as simple as the slump test; however, it is possible that tests of greater complexity than the slump test will be used on a widespread basis due to the value such workability measuring devices add to construction operations.

# CHAPTER 4—FACTORS AFFECTING WORKABILITY OF CONCRETE

## 4.1—Introduction

The workability and rheological properties of concrete are influenced by nearly every aspect of the mixture proportions, material characteristics, and construction conditions. The effects of many of these factors on workability and slump are well known and widely reported. Less data exist for concrete rheology. Widely available mixture proportioning methods often take some, but not all, factors into account. This chapter presents an overview of the influence of key factors on both workability and rheology.

The factors influencing concrete rheology and workability, as quantified by yield stress and plastic viscosity of concrete, are summarized in Table 4.1. Rheology depends on the concentration, shape, and particle-size distribution of the various solid constituents as well as the use of chemical admixtures. Due to the wide variation in materials available for concrete production and the infinite number of possible combinations of these materials, the information contained herein applies only to general cases. For specific combinations of materials, trial batches can be tested to confirm trends.

**Table 4.1—Summary of factors influencing concrete rheology and workability**

| | Yield stress | Plastic viscosity |
|---|---|---|
| **Cement content** | Decrease | Decrease |
| **Aggregates** | | |
| Aggregate volume fraction | Increase | Increase |
| Sand-aggregate volume | Optimum value | Optimum value |
| Shape | Round or cubical preferred to flat, elongated, or angular | |
| Texture | Smooth preferred to rough. Increase for high and/or very high aggregate volume concentration | |
| Gradation | Uniform gradation, high packing density preferred | |
| Microfines content | Mixed | Mixed |
| **Admixtures** | | |
| Water-reducing admixtures | Decrease | Mixed |
| Air-entrainment agent | Mixed | Decrease |
| Viscosity-modifying admixture | Increase | Increase |
| **Supplementary cementitious materials** | | |
| Fly ash | Decrease | Mixed |
| Silica fume (low dosage) | Decrease | Decrease |
| Silica fume (high dosage) | Increase | Increase |
| Slag cement | Mixed | Increase |
| **Fiber reinforcement** | Increase | Increase |

The generalization of trends in rheology, even for a change in a single factor while leaving all other factors constant, is fraught with complications. First, a trend in rheology for one variable is also a function of other characteristics of the concrete mixture. For instance, the use of an admixture may have a certain effect in one particular concrete mixture, but have a reverse effect when used in a separate concrete mixture of a different composition. Second, the interactions between different admixtures can be significant. Third, materials from different sources—or even the same source—can vary widely in composition and physical characteristics. A trend drawn from data for a single material source—such as fly ash, ground granulated blast-furnace slag, or aggregate—can not be extended to all fly ashes, all slag cements, or all aggregates of a particular mineralogy. Fourth, rheological measurements can be a function of measurement technique. As shown by Ferraris and Brower (2001), the rheological parameters measured by different concrete rheometers, even on the same concrete, can vary between different rheometers. Finally, the historical lack of suitable techniques for quantifying concrete rheology has resulted in a lack of data in the literature on the effects of various factors on concrete rheology. While some factors, such as high-range water-reducing admixture (HRWRA) dosage, have been reported widely, others have been reported scarcely, if at all. A broad range of data from various sources is desirable for drawing general conclusions.

The effects of chemical admixtures and supplementary cementitious materials are often described in terms of cement paste rheology. By measuring only cement paste, the influence of aggregates can be eliminated, and smaller mixtures can be tested. The role of aggregates is important, however, in relating measurements from cement paste to concrete. In some cases, a trend in rheology for a particular mixture change in cement paste may be reversed in concrete (Tattersall and Banfill 1983).

## 4.2—Effects of cement

**4.2.1** *Cement content*—An increase in the cement content, at a constant water-cement ratio (*w/c*), provides more paste to coat aggregates and to fill the spaces between aggregates, resulting in improved workability. Smeplass (1994) found that an increase in cementitious materials content (cement with 5% silica fume) relative to aggregate volume resulted in a decrease in both yield stress and plastic viscosity. Sonebi (2004a,b) studied the effect of four parameters—namely, water-powder ratio (*W/P*), cement dosage, HRWRA dosage, and fly ash percentage—using experimental design plans to develop SCC. The results indicated that for given values of *W/P*, HRWRA dosage, and fly ash percentage, the increase of dosage of cement led to an increase of the slump flow for SCC and a larger decrease in plastic viscosity than yield stress (Sonebi 2004a,b).

**4.2.2** *Cement characteristics*—The chemical composition and physical characteristics of cement can significantly influence workability. Even for a single type of cement, as defined by ASTM C150 or C1157, the changes in cement characteristics will influence the rheological properties of the concrete.

Hope and Rose (1990) examined the effects of cement composition on the water demand required for a constant slump. Although the correlations between composition and water demand varied between different aggregates and mixture proportions, the authors were able to draw several conclusions. The water demand increased for cement with high $Al_2O_3$ or $C_2S$ contents, and decreased for cement with high loss on ignition, high carbonate addition, or high $C_3S$ content. The particle-size distribution of the cement was significant for concrete made with angular aggregate and less pronounced for concrete made with rounded aggregate. For the concrete with angular aggregate, the cements with a higher portion of material smaller than 10 μm exhibited higher water demand. The specific surface, however, had minimal influence on water demand.

Vom Berg (1979) determined that increasing cement fineness resulted in exponential increases in both yield stress and plastic viscosity for cement pastes.

Mork and Gjorv (1997) found that the ratio of gypsum-to-hemihydrate in cement could influence cement paste rheology. For cement with high contents of $C_3A$ and alkalis, a reduction in the gypsum-to-hemihydrate ratio resulted in a decrease in yield stress, but little change in plastic viscosity. When a melamine-based HRWRA was used, the trend was reversed, with a lower gypsum-to-hemihydrate ratio, resulting in an increase in yield stress. For cement with a lower content of $C_3A$ and alkalis, the effects of the gypsum-to-hemihydrate ratio were less pronounced. Further, a reduction in the sulfate content from 3 to 1% resulted in a decrease in both the yield stress and plastic viscosity.

## 4.3—Effects of water content

An increase in the water-cementitious material ratio (*w/cm*) in either concrete or cement paste results in reductions in both yield stress and plastic viscosity (Tattersall and Banfill 1983; Tattersall 1991; Mork 1996; Szecsy 1997; Erdogan 2005). The addition of water reduces the solids concentration, resulting in less resistance to flow. Workability is improved with increasing *w/cm* up to a certain point, after which segregation can become a problem.

## 4.4—Effects of aggregates

**4.4.1** *Aggregate volume fraction*—An increase in the total volume fraction of aggregate in concrete results in increases in yield stress and plastic viscosity (Szecsy 1997; Geiker et al. 2002; Erdogan 2005). Higher volume fractions of aggregates result in reduced spacing between aggregates and, thus, greater resistance to flow. The relationship between solids volume concentration and viscosity is well established for concentrated suspensions (Barnes et al. 1989).

**4.4.2** *Sand-aggregate ratio*—Workability can be improved by optimizing the sand-aggregate ratio (*S/A*). Optimum values of *S/A* exist for minimizing yield stress and plastic viscosity (Tattersall 1991; Szecsy 1997). An optimum *S/A* for yield stress may not be optimum for plastic viscosity. At high values of *S/A*, a reduction in sand content results in a reduction in the surface area of aggregates that should be coated with cement paste and, thus, a reduction in the resistance to flow. When the sand content is reduced below the optimum value, the result is a lack of fine aggregates to fill the voids between coarse aggregates and, thus, increased resistance to flow.

For tests reported by Tattersall (1991), the minimum value of yield stress occurred at an *S/A* of approximately 0.33, while the minimum value of plastic viscosity was reached at an *S/A* of approximately 0.40. The exact value was a function of *w/c*. When testing crushed limestone and river gravel coarse aggregates, Szecsy (1997) found that the minimum yield stress was achieved at an *S/A* of approximately 0.40, whereas plastic viscosity was minimized at an *S/A* of approximately 0.30. In comparison, *S/A* values of approximately 0.50 are typical for SCC.

**4.4.3** *Shape and texture*—In this section, the somewhat ambiguous term "particle shape" is considered to be overall shape (spherical, cubical, elongated) and texture (smooth, rough) and is taken as morphology at a scale sufficiently smaller than shape so that particle of identical shape but different roughness are barely visually distinguishable. Aggregate shape strongly influences concrete workability and rheology. The influence of surface texture on workability is less certain. In concentrated suspensions, any deviation from a spherical shape results in an increased viscosity (Barnes et al. 1989; Erdogan 2005). Spherical shapes are often preferable because they more readily flow past each other and have reduced specific surface area (Tattersall 1991). Quiroga (2003) found that aggregates with spherical, cubical, or rounded shapes and smooth textures required less cement and water to achieve the same slump as aggregates with flat, elongated, or angular shapes and rough textures. When gradation was held constant, aggregates with greater packing density, which is related to shape and texture, produced higher slumps. Tattersall (1991) suggested that particle shape had a greater influence on plastic viscosity than on yield stress and that texture had no significant effect on rheology. Erdogan (2005) used monosized perfect artificial sphere and cube aggregates, of both coarse and fine sizes, and reported that particle shape had a greater influence on plastic viscosity than on yield stress. Tests comparing uncoated and artificially coated glass spheres, with roughness about 1/50 of diameter, suggested that texture does not noticeably affect yield stress or plastic viscosity for particle concentrations usually encountered in concrete.

**4.4.4** *Gradation*—The gradation, or particle-size distribution, of aggregate plays a critical role in the workability and rheology of concrete. Ideally, the gradation should take into account all solids, including the cementitious particles. In concentrated suspensions, increasing the polydispersity, or spread of sizes, decreases viscosity (Barnes et al. 1989). Even when the total aggregate surface that needs to be wetted increases, polydispersivity increases particle surface-to-particle surface, reducing the resistance to flow.

Concrete produced with gap-graded aggregates, which omit most or all of certain size fractions, can be harsh and more susceptible to segregation. Quiroga (2003) found that uniform aggregate particle-size distributions required less water for a given slump than other gradations. In designing a concrete mixture, the gradation can be optimized for a variety of objectives, such as slump, packing density, uniformity, or plastic viscosity. Quiroga (2003) found that mixtures optimized for maximum packing density or slump produced harsh mixtures with poor workability and high susceptibility to segregation. Concrete mixtures above the line on the 0.45 power chart resulted in stiff mixtures, whereas mixtures below the line resulted in harsh, segregating mixtures. Therefore, Quiroga (2003) recommended selecting a gradation that strikes a balance between high packing density and uniform grading.

**4.4.5** *Microfines content*—The addition of aggregate microfines (finer than 75 μm) can improve or reduce workability, depending on the quantity and characteristics of the microfines and the composition of the rest of the concrete mixture. Like with coarser aggregates, the quantity, shape, texture, and particle-size distribution of the microfines are important in achieving improvements in workability. The addition of microfines increases the surface area that should be wetted; however, the provision of fines can improve the particle-size distribution and result in an overall improvement in flow characteristics. The single-drop test is used to predict the water demand of microfines. A droplet of water is placed on a bed of microfines, and the resulting agglomerate is removed and weighed. The ratio of the volume of the water droplet to the volume of agglomerate describes the water requirement and the packing density.

Ho et al. (2002) evaluated the addition of either limestone or granite powder in a cement paste intended for use in SCC. The limestone powder and granite powder had approximately 75 and 80% passing the No. 200 sieve, respectively, and were obtained as dust from the aggregate crushing process. In general, the replacement of cement with the inert powders at rates up to 55% reduced cement paste yielded stress and plastic viscosity. All cement paste samples incorporated one of two different HRWRAs and maintained a constant *W/P* (cement and filler). The reduction in Bingham parameters was less pronounced for the granite powder, which tended to have flat and elongated shapes.

Ghezal and Khayat (2002) examined the use of a limestone filler material with a Blaine fineness of 565 $m^2/kg$ and 97.2% of particles smaller than 45 μm. When used in SCC mixtures at rates up to 100 $kg/m^3$ (167 $lb/yd^3$), with a constant *W/P*, the limestone filler resulted in decreased yield stress and plastic viscosity. The change was most pronounced at low cement levels. The use of limestone filler also enhanced the stability of the concrete mixtures.

Quiroga (2003) found that the addition of microfines resulted in increased dosages of water-reducing admixture required to achieve a constant slump; however, the effect of microfines varied widely, with limestone microfines requiring less HRWRA than granite or traprock microfines, which had lower sphericity. The rate of increase in demand for HRWRA became significantly higher when the percentage of microfines exceeded 15% of the total fine aggregate mass.

Rogers (2006) compared the influence of partially replacing either the fine aggregate or the cement in a concrete mixture with microfines of various types and shapes. The case of fine aggregate replacement resulted in higher relative viscosities and greater flow times due to increased powder content. Reduced harshness and improved segregation resistance were also observed. The replacement by microfines of cement rather than fine aggregates was recommended when workability and cost control were important, and high strength was not required.

## 4.5—Effects of chemical admixtures

**4.5.1** *Water-reducing admixtures*—Water-reducing admixtures enhance workability by reducing the *w/cm* needed to achieve a given slump. Alternatively, they can be used to increase slump for a given *w/cm*, reduce cement content while keeping the *w/cm* constant, or some combination of the above applications. The exact effects of water-reducing admixtures depend on the chemical composition of the admixture and the mixture proportions of the concrete to which they are added. In general, however, water-reducing admixtures result in significant decreases in yield stress, while plastic viscosity typically increases or decreases modestly.

The mechanisms responsible for improving the dispersion of cement grains depend on the chemical composition of the admixture. Water-reducing admixtures may disperse cement by imparting negative charges on cement particles (electrostatic repulsion) or by physically separating cement particles (steric hindrance) (Dodson 1990; Kauppi et al. 2005). For instance, melamine-sulfonate- and naphthalene-sulfonate-based HRWRAs are generally thought to function by electrostatic repulsion, as indicated in a reduction in zeta potential (Collepardi 1998). Modified lignosulfonate-based HRWRAs have been shown to function primarily by steric hindrance (Kauppi et al. 2005). In contrast to sulfonate-based HRWRAs, polycarboxylate-based HRWRAs consist of flexible, comb-like polymers with a main polycarboxylic backbone and grafted polyethylene oxide side chains. The backbone adsorbs onto a cement particle and the nonionic side chains extend outward from the cement particle. The side chains physically separate cement particles. Polycarboxylate-based HRWRAs have been shown to function by both electrostatic repulsion and steric hindrance (Yoshioka et al. 2002; Cyr and Mouret 2003; Li et al. 2005) or only by steric hindrance (Blask and Honert 2003; Li et al. 2005; Hanehara and Yamada 1999).

Mork (1996) suggested that, in general, low-range water-reducing admixtures decreased yield stress and plastic viscosity, whereas HRWRAs decreased yield stress and increased plastic viscosity. For both types of admixtures, the changes in plastic viscosity were most pronounced at high admixture dosages. Similarly, Smeplass (1994) found that the use of HRWRAs in concrete reduced yield stress but had little impact on plastic viscosity. For cement paste, Ho et al. (2002) found that two HRWRAs decreased yield stress substantially, but resulted in minimal decreases in plastic viscosity.

Tattersall (1991) reported that the use of a lignosulfonate-based low-range water-reducing admixture in concrete resulted in a reduction in both yield stress and plastic viscosity, although the effect on yield stress was more pronounced. The decrease in these values was most pronounced at low dosages, and leveled off at higher dosages. In contrast, the use of melamine sulfonate-, naphthalene sulfonate-, and lignosulfonate-based HRWRAs in concrete all resulted in dramatic reductions in yield stress, but little change in plastic viscosity. Again, the effects of using of these admixtures was most pronounced at low dosages and decreased with increasing dosage.

Tattersall (1991) also presented data showing that the addition of an HRWRA resulted in an increase in viscosity when used in a concrete with a low sand content ($S/A$ = 0.35), but a decrease in viscosity when used in a concrete with a high sand content ($S/A$ = 0.45). The change in yield stress was approximately the same regardless of the sand content. Tattersall and Banfill (1983) suggest that at low sand contents, the flocculated cement paste separates coarse particles; therefore, when the cement is deflocculated, the coarse particles come closer together and generate greater resistance to flow. The result is an increase in plastic viscosity of the concrete in spite of the decrease in viscosity of the cement paste. In mixtures with a high sand content, the sand fills more of the space between coarse particles. As a result, a reduction in viscosity of the paste results in a reduction in the viscosity of the concrete because the coarse particles do not move sufficiently closer together.

Billberg et al. (1996) used melamine- and naphthalene-based HRWRAs and found a reduction in both yield stress and plastic viscosity. The concrete tested had an $S/A$ of 0.57 and a maximum aggregate size of 16 mm. The reduction in yield stress was greater in percentage terms—whereas the yield stress was reduced from 600 Pa to approximately 100 to 200 Pa, the plastic viscosity was reduced from 30 Pa·s to approximately 15 to 20 Pa·s.

Tattersall (1991) showed that the effects of naphthalene- and melamine-based HRWRAs depended on cement characteristics. Further, increasing the cement content increased the potency of HRWRAs.

Faroug et al. (1999) found that the effects of naphthalene- and melamine-based HRWRAs were most pronounced at a low $w/c$. The use of both types of HRWRAs in concrete resulted in decreases in yield stress and plastic viscosity. The admixtures had essentially no effect on plastic viscosity above a $w/c$ of 0.40 or on yield stress above a $w/c$ of 0.50. The decline in potency with increasing $w/c$ was attributed to the increase in the ratio of total water to adsorbed capillary and floc water. Although the plastic viscosity did not change when the $w/c$ increased to 0.50, the additional water released through the action of the HRWRAs was sufficient to cause segregation.

Sonebi (2004a,b) carried out an experimental design program to study the effect of $W/P$, which ranged between 0.38 to 0.72; cement dosage, which ranged between 60 and 216 kg/m$^3$ (101 and 364 lb/yd$^3$); fly ash dosage, which ranged between 183 and 317 kg/m$^3$ (308 and 534 lb/yd$^3$); and HRWRA dosage, which ranged between 0 to 1% by mass of powder, on slump flow and rheological parameters. The results showed that the slump flow was influenced, in order of importance, by the $W/P$, dosages of fly ash, and HRWRA, and that the increase of these parameters led to an increase in slump flow. For the yield stress, it was affected, in order of importance, by the dosage of fly ash, $W/P$, HRWRA, and dosage of cement. The plastic viscosity was influenced, in order of importance, by $W/P$, dosages of cement and fly ash, and dosage of HRWRA. The increase of HRWRA led to a reduction of yield stress and plastic viscosity.

**4.5.2** *Air-entraining admixtures*—Air-entraining admixtures improve workability, particularly for lean or harsh mixtures or mixtures with angular or poorly graded aggregates. The presence of entrained air results in a concrete that is more cohesive; however, excessive entrained air contents can make concrete sticky and difficult to finish. Air entrainment also reduces segregation and bleeding (Kosmatka et al. 2002).

Tattersall (1991) showed that the use of air-entraining admixtures in concrete reduced plastic viscosity to a much greater extent than yield stress. The change in plastic viscosity was essentially zero above an air content of 5%, although the yield stress continued to decrease at higher air contents. Likewise, Mork (1996) suggested that, in general, low dosages of air-entraining admixtures mainly reduce plastic viscosity, while higher dosages mainly result in reductions in yield stress.

In cement paste, air entrainment can increase yield stress (Tattersall and Banfill 1983). This increase is thought to be due to the apparent negative charge imparted on the air bubbles by the air-entraining admixture. This negative charge can attract hydrating cement grains, resulting in the formation of bridges between the cement grains. In concrete, the reduction in plastic viscosity is likely due to the spherical shape of the air bubbles and the increase in paste phase volume. The yield stress of the concrete is not decreased as significantly as the viscosity due to the increase in yield stress of the cement paste.

**4.5.3** *Viscosity-modifying admixtures*—Viscosity-modifying admixtures (VMAs), also known as anti-washout admixtures, are typically used in SCC or for placing concrete underwater. For SCC, VMAs are used to improve stability by reducing segregation, surface settlement, and bleeding. In underwater concrete, VMAs reduce the washout mass loss. VMAs typically increase both the yield stress and plastic viscosity. A thorough overview of VMAs and their effects on concrete is provided by Khayat (1998).

A range of VMAs with various chemical compositions is commercially available. VMAs used for concrete typically consist of water-soluble polymers, such as welan gum or cellulose derivatives. Typically, these VMAs increase the viscosity of the mixing water through a variety of mechanisms, with the precise mode of action depending on the type of polymer. Khayat (1995) describes three modes of action by which VMAs function. First, the VMA polymers adsorb onto water molecules, which causes a portion of the water to become trapped and the polymers to expand. Second, the polymers themselves develop attractive forces and block the motion of water. Third, the polymer chains intertwine at low shear rates but break apart at higher shear rates, resulting in shear thinning behavior.

The use of a VMA can result in shear-thinning, or pseudoplastic, behavior in cement pastes or mortars. This behavior is advantageous for concrete because the relatively high viscosity at low shear rates prevents segregation of aggregates, while the relatively low viscosity at higher shear rates ensures excellent deformability during mixing, pumping, and placing operations. VMAs also increase thixotropy.

**4.5.4** *Set-accelerating and set-retarding admixtures*—Retarding and set-accelerating chemical admixtures, whose sole function is to alter the setting time of concrete mixtures, can have a profound effect on concrete rheology, depending on the chemical composition, addition rate, and time of addition of the admixture, along with the binder composition (portland cement and supplementary cementitious materials). Unlike dual-functioning water-reducing retarding and water-reducing set-accelerating admixtures, the common application of the purely set-altering admixtures do not usually affect the initial workability of concrete mixtures, but rather workability retention over a specified time period.

**4.5.4.1** *Set-retarding admixtures*—Chemical admixtures that simply retard the setting process of cementitious mixtures are designated as Type B under the classification scheme per ASTM C494/C494M. Common chemical agents that provide set performance consistent with Type B requirements include sugars such as dextrose and sucrose (often in the form of molasses), phosphonates, borates, phosphates, fluorates, and selected multivalent salts (that is, zinc and lead salts). With the ability to decrease the rate of cement hydration and lengthen set time, retarders are commonly used to offset the set-accelerating effect attributed to hot weather conditions and the higher temperatures associated with large masses of concrete. Another useful application is for maintaining workability for extended transport times and delays in placing.

Set-retarding admixtures are commonly used in conjunction with normal water-reducing admixtures, mid-range water-reducing admixtures, and HRWRAs to provide the required workability retention. With a particular set of concrete materials, concrete producers can often establish a correlation between the dosage rate of retarding admixture and workability retention. The mechanism of retarders that provides the capability to extend workability (slump retention) is essentially based on their ability to significantly reduce cement hydration through one of three proposed mechanisms:

1. Adsorption on the surface of cement hydration products (Young 1970);
2. Precipitation of insoluble hydration products (Suzuki and Nishi 1959); and
3. Complex formation (Tapin 1962; Young 1968, 1972; Daugherty and Kowalesky 1968).

All three mechanisms serve to prevent the formation of a network of hydration products, which in turn would result in a decrease in workability.

A number of important factors should be considered when using retarding admixtures.

1. The manufacturer's recommendations concerning dosage rates should be consulted;
2. The time of addition can have a dramatic effect on both set retardation and workability retention, where a delayed addition of retarding admixture (that is, addition of the admixture after the initial mixing of cement and water) normally increases retarding capability;
3. Under certain circumstances, a severe overdose of retarder can have an accelerating effect on cement hydration, and actually contribute to rapid slump loss (Daugherty and Kowalesky 1968; Ramachandran 1972);
4. Use of an ASTM C494/C494M Type B retarding admixture with either Type D water-reducing-retarding or Type G superplasticizing-retarding admixtures can result in excessive retardation;
5. Certain interactions between selected cements, admixtures, and mode of addition can result in abnormal early stiffening (workability loss), which can probably be ascribed to two processes (Seligman and Greening 1964): a) rapid acceleration of the aluminate phases, and b) altering the availability of sulfate resulting in either false or flash set;
6. The dosage of retarding admixtures often needs to be adjusted when slower-reacting supplementary cementitious materials are used as partial replacement for portland cement; and
7. When changing any material in a particular mixture proportion, especially the binder and chemical admixtures, testing is recommended to understand impact on setting time and workability retention.

Further, including multiple addition rates of the retarding admixture in the series of trial concrete mixtures can be very useful to understand the correlation between dosage, workability retention, and setting time.

**4.5.4.2** *Set-accelerating admixtures*—Chemical admixtures whose sole function is to accelerate the setting process of cementitious mixtures are designated as Type C under the classification scheme per ASTM C494/C494M. Commonly used chemical agents that provide set performance consistent with Type C requirements include the sodium and calcium salts of chloride, nitrate, nitrite, formate, and thiocyanate. These salts are often formulated with certain alkanolamines, such as triethanolamine. While set accelerators have the ability to increase the rate of cement hydration and shorten set times, these admixtures normally have little or no effect on workability, especially at the manufacturer's recommended dosages used for concrete temperatures over a range of approximately 4 to 15 °C (40 to 60 °F). When accelerator products are used at dosages suitable for antifreeze concrete applications and protection from freezing down to approximately –5 °C (23 °F) is required, early hydration can be dramatically increased, causing rapid formation of hydration products, and resulting in rapid loss of workability. For this application, ASTM C494/C494M Type F or even Type G HRWRAs are needed to allow normal handling of the concrete (Jeknavorian et al. 1994; Korhonen et al. 1997). The following practices can help minimize unexpected changes in concrete workability when using set-accelerating admixtures:

1. Unlike set-retarding admixtures, the time of addition may have only a minor effect on both set acceleration and workability retention;
2. When using an ASTM C494/C494M Type C set-accelerating admixture with either Type A water-reducing admixture or Type F HRWRA, the addition sequence should have the set accelerator being added after the other admixtures; and
3. When changing any material in a particular mixture proportion, especially the binder and chemical admixtures, testing is recommended to understand the impact on setting time and workability retention.

Further, including multiple addition rates of the set-accelerating admixture can be useful for understanding the correlation between the dosage rate of admixture, workability retention, and set time.

## 4.6—Effects of supplementary cementitious materials

**4.6.1** *Fly ash*—The use of fly ash improves the workability of concrete by reducing the water content needed to achieve a certain slump. In terms of rheology, fly ash reduces yield stress, but has variable effects on plastic viscosity. The influence of fly ash depends on whether the cement is replaced with fly ash on a mass or volume basis.

Tattersall (1991) showed that the use of a mass replacement of fly ash in concrete mixtures resulted in a reduction of yield stress, while the plastic viscosity decreased only slightly. The magnitude of reduction in yield stress depended on the initial cement content, with fly ash having the greatest improvement at lower initial cement contents. When fly ash was replaced on a volume basis instead of a mass basis, the changes in yield stress and plastic viscosity were doubled, suggesting that the increased surface area played a larger role in the incremental difference in volume between the mass and volume replacements.

Szecsy (1997) found that a 10% fly ash mass replacement level in concrete mixtures resulted in an increase in yield stress. From 10 to 20%, the use of fly ash reduced the yield stress. The use of 5% fly ash resulted in a reduction of plastic viscosity; however, further replacement of cement with fly ash at rates up to 20% resulted in little additional change in plastic viscosity.

Sonebi (2004a,b) investigated the effect of fly ash on workability and rheological parameters to produce medium-strength SCC. The incorporation of a high volume of fly ash up to 220 kg/m$^3$ (371 lb/yd$^3$) resulted in a reduction in dosage of cement required to achieve any given slump flow, viscosity, passing ability, resistance to segregation, and compressive strength. The increased dosage of pulverized fly ash (PFA) reduced the amount of HRWRA required to maintain any given filling ability and passing ability, and decreased both the yield stress and plastic viscosity (Sonebi 2004a,b).

The effects of fly ash on workability may be due to the spherical shape of fly ash particles and the effect of fly ash particles on the particle size distribution of the combined powders. It is well established that spherical particle shapes enhance the rheology of concentrated suspensions (Barnes et al. 1989). Incorporating fly ash particles with a different particle size distribution than that of cement may improve the overall powder particle size distribution (increased polydispersity), resulting in improved flow properties (Barnes et al. 1989; Farris 1968). Separately, Helmuth (1987) suggested that the spherical shape of fly ash particles is not responsible for the improvement in workability associated with fly ash. Instead, he suggested that negatively charged very fine fly ash particles adsorb onto and cover positively charged areas of cement particles, resulting in a dispersion of cement particles.

**4.6.2** *Silica fume*—The use of silica fume can improve workability when used at low replacement rates, but can reduce workability when added at higher replacement rates. The addition of 2 to 3% silica fume by mass of cement can be used as a pumping aid for concrete (Tattersall 1991). Like fly ash, the spherical shape of silica-fume particles is advantageous for workability. Due to silica fume particles being significantly smaller than cement particles, a small volume of silica fume particles may enhance the powder particle size distribution, whereas a large volume of silica fume may result in a worse powder particle size distribution. When properly dispersed with an HRWRA, the silica fume particles can increase packing density, resulting in an improvement in workability.

According to Tattersall (1991) and Mork (1996), a threshold value of the silica fume replacement level exists for concrete mixtures, such that below the threshold value, the use of silica fume reduces plastic viscosity, but produces little change in yield stress. Above the threshold value, both yield stress and plastic viscosity increase with increasing levels of silica fume replacement.

Faroug et al. (1999) measured the rheology of concrete with the silica fume used as either a replacement or addition to cement. When used as a replacement, the yield stress increased with increasing replacement levels up to 20%, above which further silica fume replacement resulted in a reduction in yield stress. The plastic viscosity decreased up to a 10% replacement, but then began increasing at higher replacement rates so that the plastic viscosity was approximately unchanged from the control at a 15% replacement rate and higher than the control at replacement rates up to 30%. When used at levels up to 10%, silica fume resulted in increased yield stress across the tested range. Plastic viscosity increased at levels up to 7.5%, above which it began to decrease.

Shi et al. (2002) tested mortar mixtures and found that the addition of silica fume resulted in a reduction in both yield stress and plastic viscosity at replacement rates up to 6 and 9%, respectively. At higher rates, yield stress and plastic viscosity increased, such that at a 12% replacement rate, both yield stress and plastic viscosity were higher than for the control mixture.

**4.6.3** *Slag cement*—Slag cement generally improves workability; however, its effect can vary depending on the characteristics of the concrete mixture in which it is used. According to Tattersall (1991), the effect of slag cement on workability is much less than that of fly ash for cases when a constant slump is maintained.

Tattersall (1991) reported results showing that the effect of slag cement on rheology was strongly dependent on the cement content and slag cement type. For a low cement content (200 kg/m$^3$ [337 lb/yd$^3$]), the addition of slag reduced yield stress and increased plastic viscosity for the two slags, which were used at replacement rates of 40 and 70%. At a higher cementitious materials content (400 kg/m$^3$ [674 lb/yd$^3$]), the use of one slag resulted in minimal change in rheology, while the use of the other slag resulted in increases in yield stress and plastic viscosity. The water content was held constant when the cementitious materials content was changed; therefore, the *w/cm* decreased as the cementitious materials content increased.

**4.6.4** *Effects of fibers*—Steel or synthetic fibers can decrease concrete workability and increase thixotropy. Tattersall (1991) showed that increasing the content of steel or synthetic fibers resulted in increases in both yield stress and plastic viscosity. For the steel fibers, increasing the fiber length resulted mainly in an increase in yield stress, but little change in plastic viscosity.

## 4.7—Effect of mixing procedure

According to Tattersall and Banfill (1983), the degree of uniformity of concrete, which influences the workability of fresh concrete, depends on the mixer design and the method of loading of the aggregates, cement, and water. Although there are no reported correlations between the mixing procedure and the Bingham rheological properties, one can anticipate that an increase in the mixing time will enhance the dispersion of fine particles, resulting in decreases in yield stress and plastic viscosity. Changing the mixing order without changing the mixture proportions or the total mixing time is also expected to affect the rheological properties. An evaluation was conducted for two trials, with each batch mixed differently: 1) mixed fine and coarse aggregate for 1 minute, added the cement and continued the mixing for another minute, then added the water and continued the mixing for 2 minutes; and 2) mixed fine and coarse aggregate for 1 minute, added half of the water and continued to mix for 1 minute, added the cement and continued to mix for another minute, then added the remaining water and continued mixing for 1 minute. This testing resulted in the second mixture being nonuniform compared with the first mixture, whereas the first mixture had a higher yield stress and plastic viscosity.

## 4.8—Effects of temperature and time

**4.8.1** *Effect of temperature*—The temperature of fresh cement-based materials has a marked effect on several key properties of the plastic material, including water demand, HRWRA demand, interaction between the binder and chemical admixtures, hydration kinetics of cement and its influence on setting and development of mechanical properties. Changes in temperature can influence the rheology of cement paste through various mechanisms, such as the rate of adsorption of HRWRA. The concentration of the residual HRWRA has a direct effect on the rheology of the cement paste and the hydration kinetics of the cement. Jolicoeur et al. (1997) showed that the concentration of adsorbed polynaphtalene sulfonate-based HRWRA and residual polymer remaining in the aqueous phase can vary with the temperature of the cement paste. The interaction of cement with other admixtures, such as viscosity-enhancing admixtures and HRWRAs, could lead to loss of fluidity or delay in setting.

Golaszewki and Szwabowski (2003) reported that the rheological properties of mortars made with polynaphtalene sulfonate HRWRAs are strongly influenced by temperature. An increase in mixture temperature can lead to an increase in yield stress and a decrease in plastic viscosity. For mortars prepared at a *w/cm* of 0.40 and HRWRA dosage of 2.25% by mass of the binder, and at a *w/cm* of 0.50 and 1% HRWRA, an increase in temperature of 10 to 40 °C (50 to 104 °F) was shown to result in a higher rate of increase of yield stress with time. The rate of increase in yield stress varied for different types of binder systems.

Figures 4.1 and 4.2 show typical changes in yield stress and plastic viscosity, respectively, with temperature (*T* expressed in Kelvin) for mortar mixtures tested at various temperatures (Petit et al. 2006). The micromortars were based on SCC mixtures of different mixture compositions, binder types, water-to-binder ratio (*W/B*), and temperature. The mixture with a *W/B* of 0.42 contained blended fly-ash-silica fume binder, while the mixture with a *W/B* of 0.52 used blended cement containing slag cement and limestone filler for the binder. The results in Fig. 4.1 and 4.2 indicate that, unlike the yield stress, plastic viscosity increased with the decrease in temperature. This was especially the case for the micromortar made with a *W/B* of 0.42 compared with that having a *W/B* of 0.52.

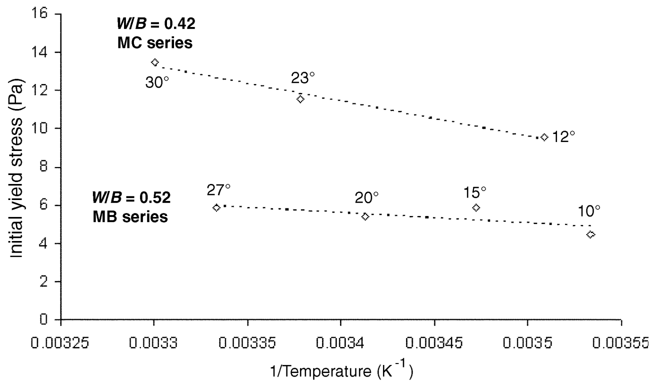



*Fig. 4.1—Changes in initial yield stress with reciprocal temperature of micromotor mixtures proportioned with* W/B *of 0.42 and 0.52 (Petit et al. 2006) (1000 Pa = 0.145 psi).*

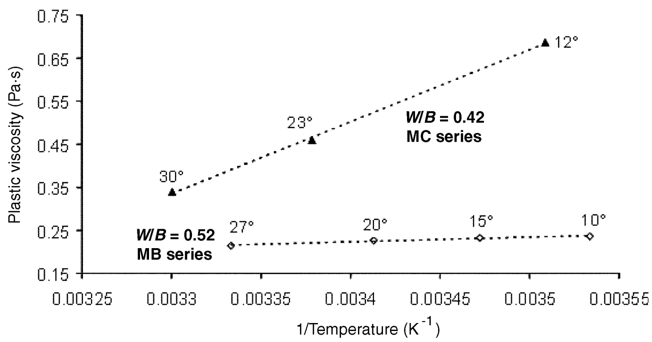



*Fig. 4.2—Variations in initial plastic viscosity with reciprocal temperature of micromortar mixtures proportioned with* W/B *of 0.42 and 0.52 (Petit et al. 2006) (1 Pa·s = 1000 cs).*

Petit et al. (2006) evaluated the combined influence of temperature and time on the variations of rheological properties of cement-based materials. Rheological parameters were monitored up to the end of the dormant period, which was evaluated using heat-flux measurements. The evolution of yield stress of micromortar with time and temperature was shown to vary in a linear fashion up to the end of the dormant period, $t_f$, and could be expressed as follows

$$\tau_o(t) = \tau_o(0, T) + \Delta\tau_{eq} \cdot \alpha \cdot e^{\beta/T} \cdot t \tag{4-1}$$

where $\tau_o(0,T)$ is the initial yield stress at a given temperature $T$; $t$ is the elapsed time; and $\Delta\tau_{eq}$, $\alpha$, and $\beta$ are experimental constants.

The plastic viscosity of micromortar also increases in a linear fashion with time and temperature, as follows

$$\mu(t) = \mu(0, T) + \Delta\mu_{eq} \cdot \gamma \cdot e^{\delta/T} \cdot t \tag{4-2}$$

where $\mu(0, T)$ is the initial plastic viscosity, and $\Delta\mu_{eq}$, $\gamma$, and $\delta$ are experimental constants.

Petit et al. (2006) also evaluated the influence of temperature on the variations of rheological properties of SCC in time.

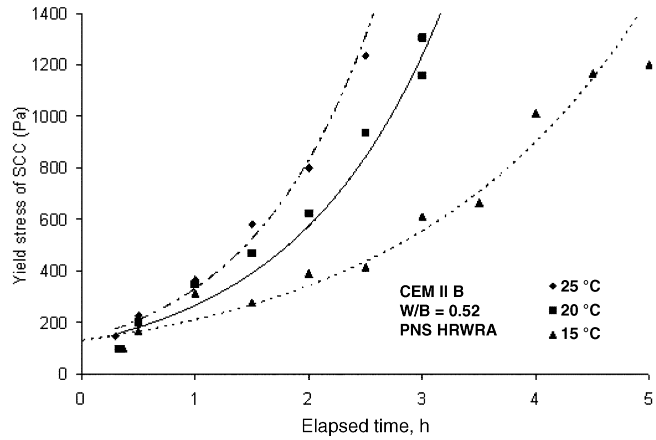



*Fig. 4.3—Variations in yield stress with time of SCC tested at various temperatures ([°C × 9/5] + 32 = °F).*

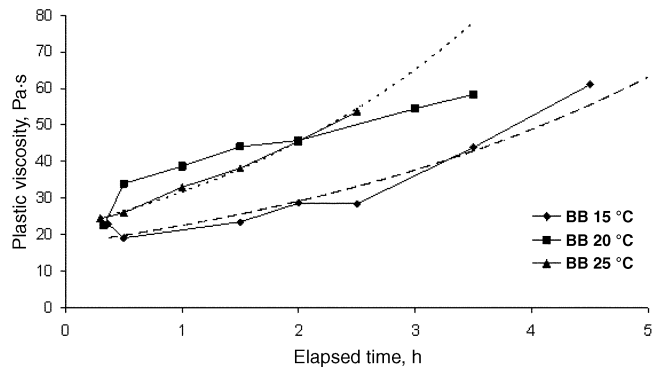



*Fig. 4.4—Variation in plastic viscosity with time of SCC tested at various temperatures (1 Pa·s = 1000 cs; [°C × 9/5] + 32 = °F).*

Figures 4.3 and 4.4 show examples of variations in yield stress and plastic viscosity, respectively, of SCC made with a *W/B* of 0.52 and blended cement containing slag cement and limestone filler. The yield stress had limited variation initially; however, considerable spread in yield stress was obtained with increased elapsed time. This was due to the accelerating effect of temperature on cement hydration, which has considerable influence on the yield stress and a lesser effect on plastic viscosity.

**4.8.2** *Coupled effect of temperature and elapsed time*—Both temperature and elapsed time affect hydration kinetics of the cement and, hence, rheological properties. To consider the variation in rheological parameters during the dormant period of cement hydration, Petit et al. (2006) proposed normalizing the elapsed time to the time corresponding to the end of the dormant period $t_f$. The time $t_f$ is taken as the time corresponding to the first deviation from linearity established of the heat-flux measurements. The data presented in Fig. 4.3 and 4.4 are replotted interns of the normalized time $t'(t' = t/t_f)$ in Fig. 4.5 and 4.6, respectively. The exponential evolution of yield stress with the normalized time, $t'$, can be described as

$$\tau_o(t') = \tau_o(0, T)e^{q \cdot t'} \tag{4-3}$$

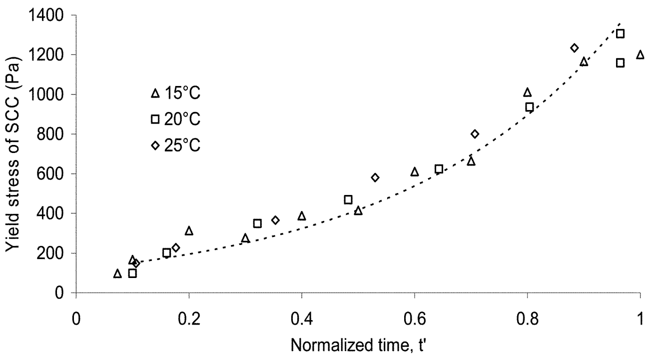



*Fig. 4.5—Increase in yield stress with normalized time for SCC tested at various temperatures.*

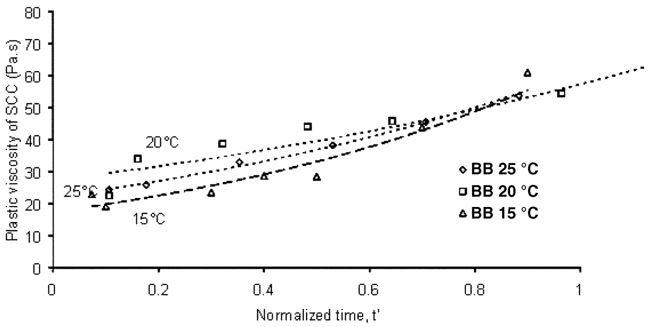



*Fig. 4.6—Increase in plastic viscosity with normalized time for SCC tested at various temperatures.*

where $q$ is an experimental constant that depends on the type of concrete and is equal to 2.4 for the tested SCC presented in Fig. 4.5. An exponential equation can also be used to describe the evolution of plastic viscosity with the normalized time $t'$, as follows

$$\mu(t') = \mu(0,T)e^{\gamma \cdot t'} \tag{4-4}$$

where $\gamma$ is an experimental constant equal to 0.94 for the tested SCC mixture.

## CHAPTER 5—EXAMPLES OF USING WORKABILITY TEST METHODS

This chapter presents five examples of the use of workability test methods to improve the performance of fresh concrete in the field. The examples include both grout and concrete mixtures that vary in workability from no-slump to self-consolidating.

### 5.1—Use of gyratory tester to measure workability of no-slump concrete

This example describes the experience of a large precast company in measuring the workability of no-slump concrete in the production of hollow-core planks, roofing tiles, and structural elements.

**5.1.1** *Background*—Traditionally, workability of no-slump concrete is measured through compactability, which is measured by the results obtained in compressive strength tests. This approach is justified in the sense that compressive strength is usually directly determined by density for a given mixture. By measuring compactability only, knowledge of workability is obtained much faster without the need to wait for the strength results.

*Fig. 5.1—Intensive compaction tester m-100R, with test cylinder and electronic pressure controller on right.*

Other potential tests for measuring the workability of no-slump concrete—modified Vebe-test, Kango-hammer, and Waltz test—are cumbersome, tedious, slow, some too noisy, and all inaccurate. Thus, they are not often used in any plant. The casting machine operator's opinion of the workability based on the appearance of the extruded or slipformed product is the most common control method: the operator takes a handful of no-slump concrete and squeezes it. This method is comparable to the so-called trowel test with normal flowable concrete.

In the late 1980s, the competition in the precast concrete industry intensified. Thus, there was a need to improve productivity and process control. One of the main problems in using no-slump concrete is to measure workability in quantitative terms (instead of an operator's qualitative opinion). This led to the further development and use of a gyratory compactor: the intensive compaction tester (IC tester) (Fig. 5.1).

The design of improved casting machines for hollow slab cores required modeling of the concrete compaction process. To model the compacting process, several numeric parameters describing the compactability of various fresh concrete mixtures were required. For this purpose, extensive laboratory work was carried out. Compared with earlier studies, the new project was able to investigate the compaction process in greater detail using new tools that improved the speed of research. The IC tester, with the ability to continuously measure shear force and with three-dimensional graphics data presentation software, made it possible to carry out more extensive tests and obtain more detailed data on the compaction of stiff freshly mixed concrete.

During a year-long test series in the laboratory and at plants, a large number of $w/c$ between 0.28 and 0.45 were analyzed, involving about 250 different concrete mixtures and a total of approximately 3000 tests with the IC tester. This section presents some of the results that provide an indication of the potential of gyratory compactors.

**5.1.2** *Lab tests*—The equipment available for the tests consisted of an IC tester with a shear force measurement feature, a laptop for data collection, a 50 L (1.8 $ft^3$) concrete mixer, and standard laboratory equipment.

The concrete was mixed in batches of 20 L (0.7 $ft^3$) in a 50 L (1.8 $ft^3$) pan mixer. Maximum care was taken in sampling, that is, in filling the IC-tester cylinders, to ensure that each sample was truly representative. This proved to be a demanding task, especially with coarse and relatively dry mixtures that had a tendency to segregate both in the mixer and in filling the cylinder.

**5.1.2.1** *Experience from using tester*—The IC tester m/88, featuring a deformation force measuring device, was the first unit of its kind available in the autumn of 1988, although less advanced units had been used by the company for a few years.

As the full potential of the equipment was not known, a large test series was carried out to measure the effect of such factors as water content, admixtures, additives, mixture proportions, aggregate grading and quality, inert and pozzolanic fillers, and operator motivation. After the laboratory test series, the obtained results were verified at selected precast plants.

**5.1.2.2** *Density measurement*—The IC tester measures the position of the compacting piston as a function of the compaction cycles and calculates the density of the sample on the basis of its predetermined mass. By selecting the mass of the sample properly, it is possible to achieve the desired height-diameter ratio, such as 1.0, for the compacted specimen.

The unit only measures the position of the piston, not the actual density of the sample. This is important for wet concrete in particular because cement paste tends to be squeezed out through the gap between the cylinder and the compaction discs toward the end of the compacting process. This means that the obtained density measurement value is too high. This can be avoided by selecting the range of applied pressure and revolutions properly or compensating the loss by weighing the lost paste. Also, any sand grains between the plate on top of the sample and the piston will give an incorrect (too low) density value for the compacted sample.

Examples of obtained density values are presented in Fig. 5.2. The curves on the upper part of the graph present density curves. All three samples were compacted to the target density of 2430 $kg/m^3$ (152 $lb/ft^3$), which represents a typical density for a certain concrete product. The samples are from the same concrete batch and, thus, the two later samples required more compaction effort due to a slight stiffening of the concrete mixture. The required compaction effort was 50 cycles for the first sample, and 62 and 80 cycles, respectively, for the later ones.

**5.1.2.3** *Shear force measurement*—Aside from density, the IC tester measures the force that resists compaction. The internal friction curve plotted on the basis of the shear force measurements has proven to be one of the best parameters to describe the characteristics and compaction of the concrete. This information also helps to verify that each measurement is performed properly. It also gives additional information about the internal friction and other related phenomena.

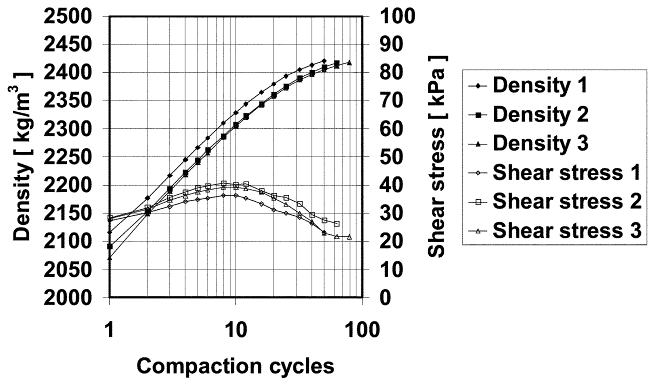



*Fig. 5.2—Compaction curves (monotonously rising) and shear stress curves.*

This information can be used in mixture proportioning and optimization.

In Fig. 5.2, the lower curves present the shear stress, which show the behavior of the concrete mixture under compaction. The aging or stiffening of the mixture due to cement reactions is visible. The maximum shear stress for the first sample is 36 kPa (5.2 psi), but 39 and 40 kPa (5.7 and 5.8 psi), respectively, for the other two.

The tester also measures and/or stores the following data:

- Test number;
- Age of concrete;
- Mass of test sample;
- Applied pressure;
- Number of revolutions used; and
- Achieved or desired density.

Some of these data are fed manually into the control unit of the tester and require care. To avoid mistakes in adjustment, an electronic pressure controller with preset values for the most common pressures should be used. This will improve the speed of adjustment and repeatability of the test.

**5.1.2.4** *User characteristics*—The tester is easy and simple to use. After reading the instructions, it takes about 15 to 30 minutes to learn how to operate.

The m/88 tester worked well. It was checked and serviced for the first time after 500 compaction samples by the manufacturer. Another inspection was carried out after 2000 samples. Maintenance was limited to cleaning, abrasion measurements, and greasing. The only components that had to be replaced consisted of the rubber seals on the rotating lower support shaft.

The only problems, or suggestions for improvement, were related to pressure adjustment (manual at the time) and daily cleaning of the unit, which have been improved in later versions.

**5.1.3** *Repeatability*—To avoid the effect of chemical reaction of cement on workability, the first tests were made with moist aggregate mixtures. The aggregate gradation was that of a typical no-slump concrete mixture, and the moisture content was 6% of the aggregate weight. The range of variation in obtained density was 17 $kg/m^3$ (1.1 $lb/ft^3$); density varied between 2239 and 2256 $kg/m^3$ (139.8 and 140.8 $lb/ft^3$) (Fig. 5.3). The standard deviation in the test with 13 consecutive samples was 5.3 $kg/m^3$ (0.33 $lb/ft^3$). This could be compared

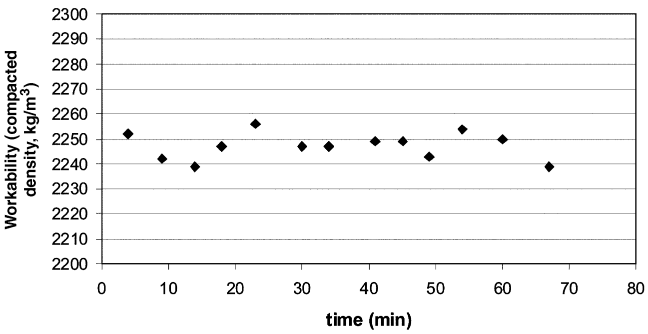



*Fig. 5.3—Repeatability of IC tester; moist aggregate mixture (1 kg/m³ = 0.036 lb/in.³).*

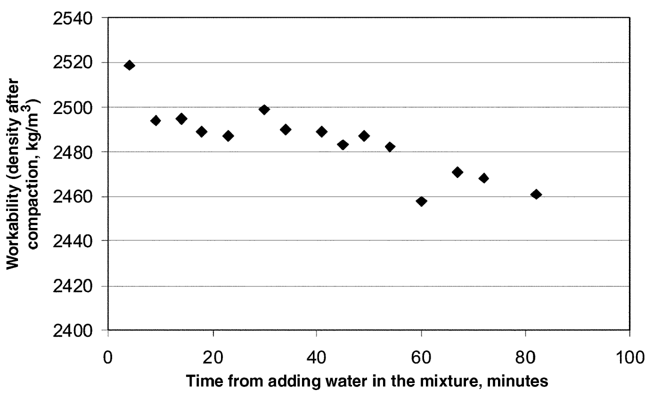



*Fig. 5.4—Effect of concrete age on workability (and compacted density) (1 kg/m³ = 0.036 lb/in.³).*

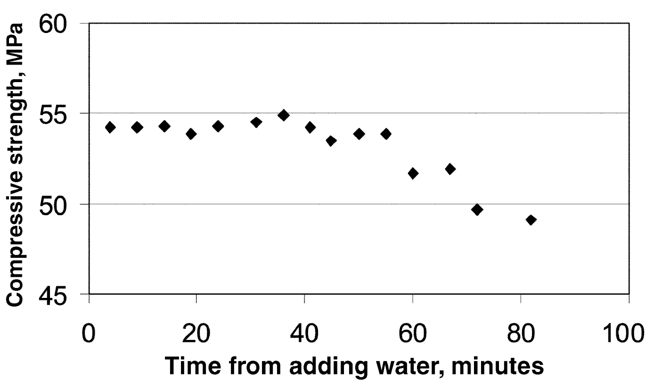



*Fig. 5.5—Compressive strength at 3 days of samples presented in Fig. 5.4 (1 MPa = 145.04 psi).*

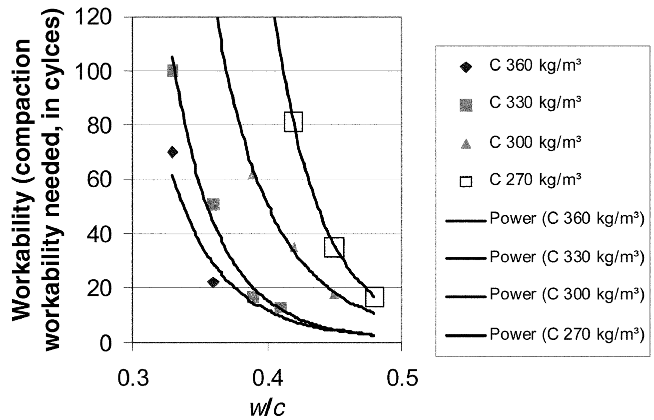



*Fig. 5.6—Effect of* w/c *on workability (1 kg/m³ = 0.036 lb/in.³).*

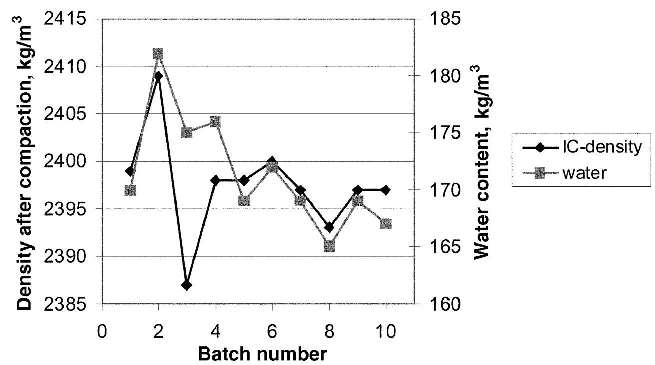



*Fig. 5.7—Workability and water content variation from batch to batch (1 kg/m³ = 0.036 lb/in.³).*

with the standard deviation of 14 kg/m$^3$ (0.87 lb/ft$^3$) in ASTM C29/C29M.

Repeatability of typical fresh concrete mixtures is subject to variation caused by aging of fresh concrete, which is due to the chemical reactions of cement (Fig. 5.4). The age of the concrete is important if the test lasts longer than 30 to 50 minutes, depending on the cement fineness and type. After this time lapse, densities obtained with constant compaction effort begin clearly to decrease as a result of chemical and physical processes taking place in the material. The very first measurement at 5 minutes after adding water will give a higher density in case of early-strength cement. In Fig. 5.4, the following values (Samples 2 to 11) are at a constant value until after 50 minutes from adding water in the mixture, after which the mixture starts to stiffen rapidly due chemical reactions in the mixture. The standard deviation in the measured density values of Samples 2 to 11 is 5.3 kg/m$^3$ (0.33 lb/ft$^3$).

The effect of aging in the workability of no-slump concrete can be seen also in the compressive strength of the samples (Fig. 5.5). The samples presented in Fig. 5.5 were tested 3 days after curing at 20 ºC (68 ºF) and 95% relative humidity.

In addition to measuring the workability, the compacted concrete cylinders can be used either to measure the fresh strength (cohesion) or stored properly for measuring the compressive or splitting strength at a selected age. If the purpose is to measure the effect of compaction, then the samples should be compacted with a constant compaction effort (such as 40 cycles at 80 kPa [11.6 psi]). If the purpose is to measure the strength properties of the concrete mixture, then the samples should be compacted to constant density.

**5.1.4** *Factors affecting workability*—An IC tester could be used to measure the effect of various factors on workability. Figure 5.6 shows the effect of *w/c* at different cement contents on the effort needed in consolidating a fresh concrete sample to a constant consolidation degree.

The effect of water content on workability is shown in Fig. 5.7. Samples from 10 consecutive concrete batches were taken at a batching plant. The water content was then measured by microwave oven drying. Simultaneously, the workability of the fresh concrete was measured by compacting a sample with a constant number of compaction cycles, and the value of obtained density was stored in the computer. In Fig. 5.7, each obtained value is from one measurement. The obtained density correlates well with the water content in the concrete mixture (although there could be other variations at the same time, such as dosing errors of different aggregate fractions and temperature variations). Sample 3 has an error. If the operator does not succeed in taking a representative sample, the obtained measurement value is typically lower than the average variation would cause. In this case, it is probable that the sample contains too many larger aggregate particles, which would cause the so-called wall effect, or that a sand grain has fallen on the top plate in the testing device.

**5.1.4.1** *Applications of IC tester*—During the first test series, workabilities of hollow core plank concrete mixtures with a *w/c* of 0.27 to 0.45 and water content of 90 to 150 L/m$^3$ (152 to 253 lb/yd$^3$) were measured. The number of revolutions varied from 10 to 800, and pressure varied from 10 to 240 kPa (1.45 to 34.8 psi). The IC tester was also used for testing the relatively wet roofing tile concrete with water content in the region of 200 L/m$^3$ (340 lb/yd$^3$).

The tester can be used for analyzing relatively wet freshly mixed concrete, provided that the pressure and the number of compaction cycles are low. A suitable range for roofing tile concrete was 10 to 20 kPa (1.45 to 2.9 psi) at 20 to 40 cycles, in which case the amount of cement paste squeezed out of the cylinder remained below 10 g (0.35 oz), which is still within the acceptable limits.

The tester was also used for analyzing the compactability of different aggregates or aggregate mixtures in connection with the investigation of compaction degree and void space. This extra information is valuable for mixture optimization.

**5.1.4.2** *Reproducibility of results*—The reproducibility of measurements is excellent. Aside from the age of the concrete, the variation in workability/density results in successive test runs depends mainly on how skillfully a laboratory technician can take representative homogeneous samples. Especially with relatively dry coarse concrete, segregation can easily occur both in the mixer and in filling the cylinder. If possible, the tests should be performed by the same person.

As a guideline, the density variation from the average was typically ±2 kg/m$^3$ (0.12 lb/ft$^3$) for roofing tile concrete, ±5 kg/m$^3$ (0.31 lb/ft$^3$) for sandy hollow core plank concrete, and ±8 kg/m$^3$ (0.50 lb/ft$^3$) for coarse-aggregate concrete and earth-moist aggregate mixtures, when the samples were taken by an experienced technician. With an inexperienced technician, variations were two to three times larger.

To achieve good reproducibility, it is necessary to keep the tester in good condition and to ensure that the pistons, compacting discs, and cylinders remain clean. Also, any grains of sand or similar contamination remaining on top of the upper compacting disc will result in an increased scatter in the data, and give incorrect results.

**5.1.4.3** *Comparison of fresh concrete mixtures*—Flowable concrete mixtures are usually compared so that reference workability is standardized by maintaining constant slump. After constant slump is maintained, the effect of variables (admixtures, additives, mixture proportions, and compaction methods) on the properties (compressive strength and durability) is compared. No similar standardized procedure for comparison of no-slump mixtures has been established for stiff concrete.

A recommended procedure is to measure the typical density of the concrete products in the process that will be analyzed or controlled. Then the compaction energy range (to simulate the equipment used in the industry, such as a hollow core slab extruder or roofing tile press) is selected by testing a certain pressure and target density combination. The typical density is then set as a target density, and workability is measured as the number of compaction cycles needed to achieve this target density.

**5.1.4.4** *Can lab results be applied to real life?*—One of the advantages offered by laboratory-grade aggregate is that it is standardized; that is, variations in quality are minimized. As a result, the number of tests can be minimized.

When trying to solve problems existing at plants, however, the aggregate currently used at the plant should be used in the tests. When this is done, the test results obtained with the IC tester at the lab have been directly applicable at the precast plants. In case of serious workability problems, the cement used at the plant should be brought to the lab for workability tests.

The laboratory staff should become familiar with, or at least be aware of, the processes and restraints in production and coordinate the procedures with foremen, batching plant operators, and casting people.

**5.1.5** *Use of IC tester in field*—After the extensive test series in 1988 in measuring workability of no-slump concrete, Consolis used IC testers as standard intercompany tools. Presently, the Consolis-group has 10 IC testers in use. Eight of the instruments are located at high-volume precast plants for measuring the workability for quality-control purposes and for process optimization. These instruments are frequently loaned to nearby sister units.

Two of the IC testers are used by research and development personnel for mixture optimization, process development, and troubleshooting. One of these is almost constantly on the move with the material technologists who are supporting the smaller production units. The IC tester is transported in a car trunk or in a mobile lab van from one plant to another. The older version weighs 55 kg (120 lb), while the newer version weighs 90 kg (200 lb); thus, they can be lifted by two persons. On the site, they are moved either by machinery, a light two-wheel cart, or carried to the selected location. The tester requires electric power and a small volume of pressurized air, which is normally available, even in field conditions. If not, then a small generator and air compressor is taken along. The setup of the tester takes about an hour, including finding a suitable location and connections to a standard electrical outlet and to a compressed air supply. Some of the testers are standard versions, while some have shear-force-measuring capability. Normal quality control does not necessarily need

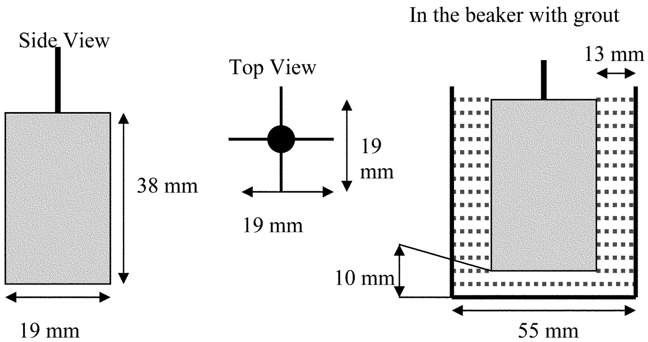



*Fig. 5.8—Schematic diagram showing dimensions of four-bladed vane spindle and beaker during testing (1 mm = 0.039 in.).*

the shear force measurement. For troubleshooting, optimization, and research purposes, the shear force measurement gives additional information, and is highly recommended. As the test takes only 3 to 5 minutes, it is possible to measure, at least for certain periods, every batch at a precast plant, if needed. The gyratory compactors—in this case, IC testers—have brought the workability measurement of no-slump concrete to a completely new level.

## 5.2—Using rheological measurements to solve problem with flooring grouts

**5.2.1** *Introduction*—Cement grouts are used for a wide range of applications in the construction industry. These grouts require a high workability, which is achieved with HRWRA.

Some cement pastes perform better (flow faster and are workable for longer times without bleed and segregation) in some countries than in others. These problems may be solved on an empirical basis when they arise. This project, however, investigated the basic mechanisms involved in order that the performance of the cement pastes might be predicted more effectively.

To do this, a relationship between the rheological properties of the cement paste and the chemical components, especially the different kinds of sulfates, of portland cement was established. First, a relationship between the simple industrial tests such as the flow cone and the rheological properties obtained by a rheometer was established. This has been reported elsewhere (Claisse and Omari 1999; Omari 2001). Subsequently, more tests were performed such as x-ray fluorescence (XRF) spectroscopy to determine the chemical composition of cement, thermogravimetric analysis (TGA) to determine the different types of sulfates, particle-size distribution, and specific surface area (SSA) tests. To relate the chemical composition to the rheological properties, 14 different cements from various countries were analyzed. A full report of the study is in the literature (Claisse and Omari 1999; Omari 2001).

**5.2.2** *Experimental methods*

**5.2.2.1** *Materials*—Cements were obtained from different commercial suppliers. Three different HRWRA admixtures were used:

- Sulfonated melamine formaldehyde (SMF);
- Sulfonated napthalene formaldehyde (SNF); and
- Lignosulfonate (LS).

**5.2.2.2** *Rheological tests: rheometer*—This test measures the viscosity and the shear stress of a cement paste. A Rheology International Series 2 viscometer Model RI:2:M was used. The viscometer was chosen with a medium spring to obtain more accurate data at low speeds. The Bingham model was used to determine the plastic viscosity and the yield value.

The rheology of Bingham plastics is not very sensitive to temperature, but the rate of change of rheology with time in a chemically reacting system containing cement is affected by temperature. It is preferable to standardize both the test temperature and the time after mixing at which the test is performed (Banfill 1994). All of the tests reported herein were performed at 20 ± 1 °C (68 ± 2 °F). The test materials were stored at this temperature for at least 48 hours before use.

A four-bladed vane spindle (Fig. 5.8) was used for this work. The vane had four rectangular blades of radius $R_v$ of 9.5 mm (0.37 in.) and a height $h$ of 38 mm (1.5 in.), and was placed in a cup of radius 27.5 mm (1.08 in.) centrally mounted on the lower plate. Because of the restricted torsion of the spring, which moves the spindle, these actual dimensions do not comply with those recommended by ASTM D2573 ($R_v$ = 19.05 mm [3/4 in.] and $h$ = 76.2 mm [3 in.]). The actual rheometer used was capable of producing comparative data on which decisions regarding mixture could be made.

The shear stress $\tau$ was calculated from the torque $T$ using the following conversion formula

$$\tau = 3T/(2\pi[R_v^3 + 3R_v^2 h]) \quad (5\text{-}1)$$

**5.2.2.3** *Testing cycle*—The testing cycle (Fig. 5.9) was chosen to stay within the restrictions of the apparatus and reduce the antithixotropic behavior that the material might have. Reducing the readings on the down-curve from 20 data points to 10 did not affect the accuracy in obtaining the yield value and the viscosity. Reducing the number of points on the down-curve helped obtain a positive value of the slope (viscosity) because shortening the cycle reduced the effect of shear-thickening (antithixotropy), which some cement pastes have. The up-curve used 20 data points to ensure that the break point could be determined more accurately.

The testing cycle was checked by performing a series of single-point tests at fixed speeds and comparing the results with a test using the normal testing cycle. The results were very similar, which indicated that they were not a product of the particular testing cycle that was used.

Figure 5.9 also shows how the viscosity, yield point, and break point are derived from the results of the cycle. Relating these to practical applications, the break point indicates how easily a mixture may be moved from a static position (resting in a pipe). The yield shows the resistance to flow (pumping pressure) at slow speeds, and the viscosity shows how the resistance to flow increases as the speed (rate of pumping) increases.

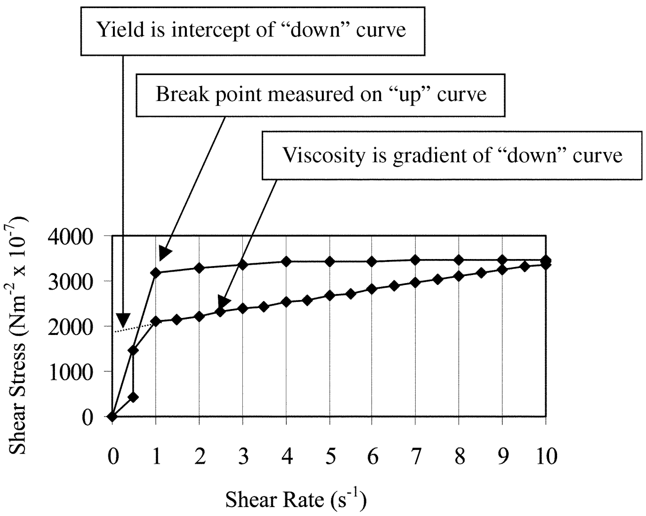



*Fig. 5.9—Testing cycle.*

**5.2.2.4** *Effect of mixing speed and time on rheological properties*—The speed of mixing affected the initial flow of the cement paste when mixed for 5 minutes. A standard mixing speed and mixing time was chosen for the final testing. A series of tests on trial samples was carried out. Different mixing speeds (900, 1100, 1300, 1500, and 1900 rpm) and mixing times (2, 3, 4, and 5 minutes) were tested. The samples were tested 3 minutes after finishing mixing.

Mixing (Fig. 5.10) for longer times (4 and 5 minutes) gave a better workability and stability for the cement pastes. Mixing for 2 or 3 minutes was inadequate, and that caused the unexpected increase of break point value with the increase of speed. Mixing at very high speeds (>1100 rpm) gave a high workability and made the cement paste too thin for the rheometer (antithixotropic behavior). Therefore, the following mixing method was used:

After pouring all the material into the mixing beaker, while the mixer's spindle was rotating at 1100 rpm, the timing was started. After 40 seconds, the speed was raised to 1900 rpm for 20 seconds to ensure that all the lumps were broken. The speed was reduced to 1100 rpm for 2 minutes and 40 seconds (that is, 160 seconds), and again raised to 1900 rpm for 20 seconds. Finally, the speed was lowered to 1100 rpm for 1 final minute of mixing. This made the total mixing time equal to 5 minutes. When not using any water-reducer or when using lignosulfonate WRA, the mixing speed was kept at 1900 rpm for the entire 5 minutes to ensure that the material would be workable enough for the rheometer. This mixing method was used to ensure that no lumps would form and the cement paste would be properly mixed.

Relating this mixing to the methods used in practice is difficult because no shearing was used. In a commercial grout mixer, the pumping action will shear the mixture; this will provide effective mixing at relatively low speeds. In concrete, the aggregate will shear the paste during mixing.

**5.2.2.5** *Standing time of cement paste*—The standing time of the cement paste before testing affected its rheological properties. Three samples were tested at different standing times: 0.5, 1, 2, 3, and 4 minutes. Increasing the standing time increased the yield value (Fig. 5.11 and 5.12). A standing time of 1 minutes was chosen to give enough time to load the sample into the rheometer and start testing.

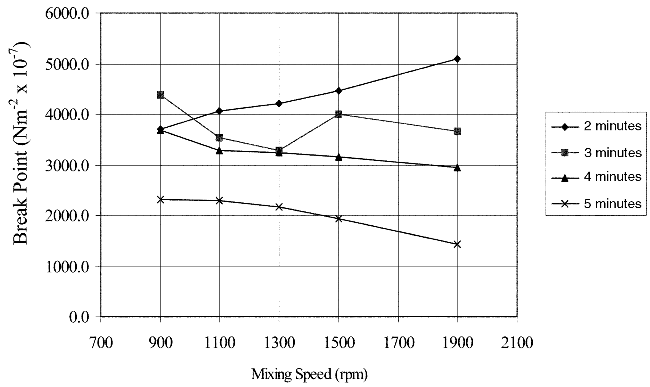



*Fig. 5.10—Effect of mixing speed and mixing time on rheology of cement pastes.*

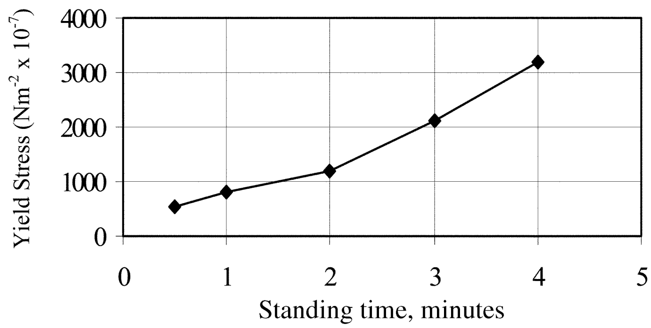



*Fig. 5.11—Standing time determination using SMF.*

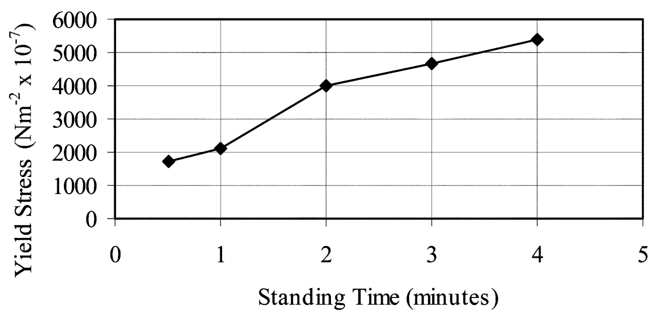



*Fig. 5.12—Standing time determination using SNF.*

**5.2.2.6** *Mixture proportions*—After studying all the initial tests, the final mixture proportions were chosen as follows:

| | |
|---|---|
| Blank sample without water-reducing admixture | |
| Cement | 100% |
| *w/c* | 0.50 |
| | |
| SNF/SMF sample | |
| Cement | 99.70% |
| SNF/SMF | 0.30% |
| *w/c* | 0.40 |
| | |
| LS sample | |
| Cement | 99.70% |

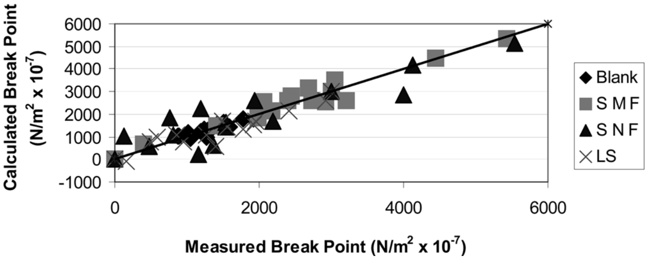



*Fig. 5.13—Model for break point (1 kN/m$^2$ = 0.14 lb/in.$^2$).*

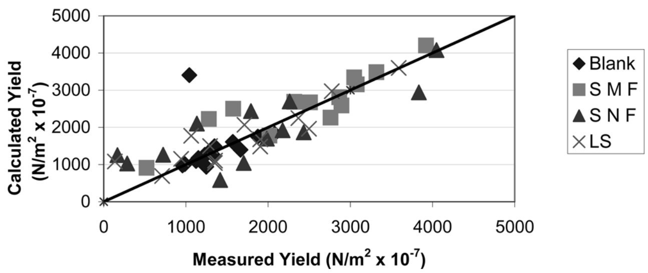



*Fig. 5.14—Model for yield (1 kN/m$^2$ = 0.14 lb/in.$^2$).*

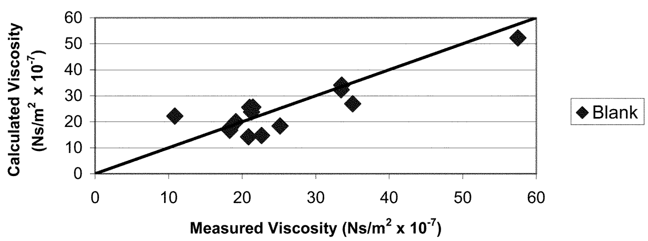



*Fig. 5.15—Model for viscosity (1 kN·s/m$^2$ = 0.14 lb·s/in.$^2$).*

| | |
|---|---|
| LS | 0.30% |
| *w/c* | 0.45 |

The amount of powder used in the samples was 300 g (10.6 oz).

**5.2.3** *Results*—The chemical and physical properties of the cements were correlated to the rheological properties of cement pastes using statistical computer programs. The flow of cement paste is dependent mainly on SSA and particle-size distribution, which is correlated to SSA. The effect of SSA was removed to reveal other factors, which could affect the flow. The other main factors were removed in turn. The most important factor to consider when building a model is the level of significance (P-value) of each estimated coefficient—the lower the P-value, the more significant the contribution of that variable to the model. A 0.05 P-value indicates a 5% probability that the relationship between two variables could have happened by chance. The highest acceptable level of significance in the present analysis was 0.05.

Multiple regression could sometimes suggest spurious relationships between variables, particularly where the independent variables are highly correlated. Care was taken to ensure that relationships could be supported by experimental evidence. Precautions were also taken against the danger of building a theory on one or two pieces of influential data, which could be rogue values or outliers.

The final flow models for the break point were (Fig. 5.13):

- Break point (blank) (Pa) =
  –1171(Pa) + 1178 Hemihydrate% (Pa) + 6 SSA (Pa·kg/m$^2$)
- Break point (SMF)(Pa) =
  –7205(Pa) – 22,380 $Cr_2O_3$%(Pa) –10,890 $Na_2O$%(Pa) + 1242 $Al_2O_3$% (Pa)+ 17 SSA (Pa·kg/m$^2$)
- Break point (SNF)(Pa) =
  – 20,344(Pa) + 2343 $Al_2O_3$%(Pa) + 31 SSA (Pa·kg/m$^2$)
- Break point (LS)(Pa) =
  –6244(Pa) –24,468 $Cr_2O_3$%(Pa) + 1128 $Al_2O_3$%(Pa) + 7 SSA(Pa·kg/m$^2$)

The final flow models for the yield value were (Fig. 5.14):

- Yield (blank) (Pa) =
  –1259(Pa) + 1352 Hemihydrate% (Pa) + 6 SSA(Pa·kg/m$^2$)
- Yield (SMF)(Pa) =
  –8999(Pa) – 26012 $Cr_2O_3$%(Pa) + 1228 $Al_2O_3$%(Pa) + 17 SSA(Pa·kg/m$^2$)
- Yield (SNF) (Pa) =
  –17,278(Pa) + 1965 $Al_2O_3$%(Pa) + 28 SSA(Pa·kg/m$^2$)
- Yield (LS) (Pa)=
  –10,504(Pa) + 1138 $Al_2O_3$%(Pa) + 19 SSA(Pa·kg/m$^2$)

The final flow model for the plastic viscosity was (Fig. 5.15):

- Plastic viscosity (blank) [Pa·s] =
  77(Pa·s) + 50 Hemihydrate% (Pa·s) – 14 $Al_2O_3$%(Pa·s)

No models for plastic viscosity for the superplasticized samples could be developed.

**5.2.4** *Discussion*—The main observations from these results are:

- Plastic viscosity alone does not reveal the significant trends in the data. A full rheological analysis, including yield and break point, is necessary to understand the system;
- The present results do not indicate that any given factor does not have an effect on results—they only indicate that it is not an effect that is statistically significant at the 5% level;
- It is not indicated that the effect of sulfate morphology (that is, the relative amounts of gypsum, hemihydrate, and anhydrite) is very significant. The hemihydrate is only significant where no admixtures are used. This partially contradicts the findings that were indicated in the literature and the preliminary work; however, these results refer to total amounts present rather than the amounts in solution. Another factor (the chromate discussed as follows) could be controlling solubility and, thus, be more significant;
- The aluminate phases have a significant impact on rheology, which was expected from the literature; and
- An unexpected effect of the chromate phases was observed. A brief additional experimental program was carried out to investigate this observation.

Blue Circle Wardale (BCW) cement was chosen to study the effect of various levels of $Cr_2O_3$ (0, 0.05, 0.07, 0.10, 0.15, and 0.20%) on the flow. This particular cement was chosen because it contains no $Cr_2O_3$. All mixtures were

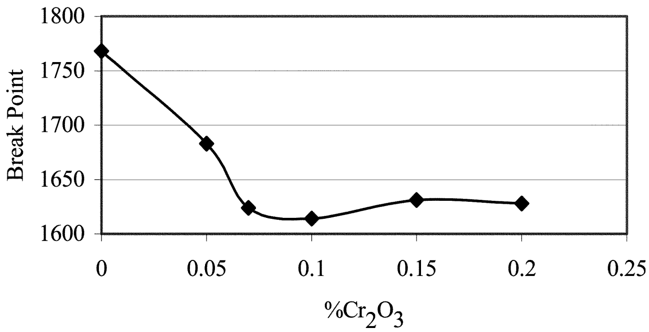



*Fig. 5.16—Effect of $Cr_2O_3$ on the beak point.*

performed using the standard mixing method used for the blank mixture. Figure 5.16 illustrates the effect of $Cr_2O_3$. These experimental results suggest that the significant relationship between break point and $Cr_2O_3$ found by statistical analysis is genuine (Fig. 5.16). Chromates are known to be retarders and, in some cements, special measures are taken to reduce the adverse effects of $Cr^{VI}$ by reducing it to $Cr^{III}$. Further investigation would be required to determine how this would affect the models for their workability when HRWRA is added. In particular, the effect of chromates on sulfate solubility may be significant.

**5.2.5** *Conclusions*

- The most significant effects were not revealed by a simple study of viscosity. Several rheological parameters were needed;
- For all cementitious mixtures, the SSA of the cement had the greatest influence on workability;
- For cementitious paste mixtures without admixtures, the hemihydrate content had a significant effect on workability;
- For cementitious mixtures with SMF, SNF, or LS admixtures, the workability generally increased with decreasing aluminate content; and
- For mixtures with SMF and LS admixtures, the workability generally increased with increasing chromate content.

## 5.3—Measuring batch-to-batch consistency of self-consolidating concrete

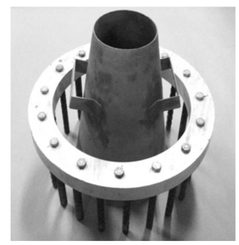
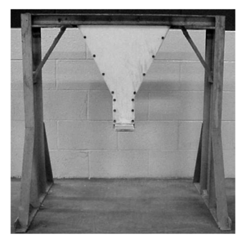
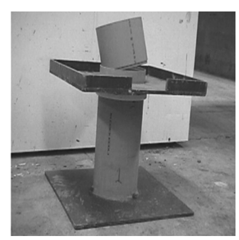
Concrete manufacturing operations need to maintain batch-to-batch consistency of fresh concrete properties. Batch-to-batch concrete reproducibility is often tested by measuring slump. In the case of SCC mixtures, the slump measure is not sufficient to characterize batch-to-batch consistency completely.

This example describes how several test methods were used to determine reproducibility of production of SCC batches.

**5.3.1** *Sample preparation and methods*—Two days were spent obtaining and testing samples of SCC mixtures used in production. Table 5.1 describes the test methods used and the SCC properties that were evaluated.

**5.3.2** *Results*—The specific mixture proportions were fixed for all test batches and raw materials were the same for all mixtures. Table 5.2 provides the data recorded during the 2 days of batch-to-batch testing.

**Table 5.1—Test methods for SCC**

| Characteristics | Test method | Description |
|---|---|---|
| Filling ability (deformability) and stability | Slump flow/VSI  | For slump flow, refer to Section 3.3.2.7. The VSI is determined by rating the apparent stability of the slump flow patty. |
| Passing ability | J-ring  | Refer to Section 3.3.2.3. For this study, the difference in spread between the J-ring measure and the standard slump flow measure was used to determine passing ability. |
| Relative viscosity | V-funnel  | Refer to Section 3.3.2.9. The flow time for all of the concrete to exit the funnel is recorded as a measure of filling ability. For SCC, the flow time should be less than 10 seconds. |
| Stability | Column segregation  | Refer to Section 3.3.1.3.7. The lower the segregation ratio, the greater the stability of the sample. |

Statistical data was generated on the batches tested to evaluate production consistency. Table 5.3 contains that data.

**5.3.3** *Conclusion*—Other than the slump flow from the first batch tested on 4/27/04, the consistency and control of the production SCC mixtures were found to be good. SCC properties, such as viscosity, passing ability, and segregation resistance, cannot be evaluated with a single slump measurement. Multiple measures of SCC properties can ensure that batch-to-batch consistency of SCC properties is maintained.

## 5.4—Troubleshooting self-consolidating concrete mixtures

**5.4.1** *Introduction*—An architectural precast producer was implementing the use of SCC into its facility. During the implementation process, several difficulties were experienced. A series of laboratory trials was conducted in an effort to

**Table 5.2—Test data**

| Mixture date | 04/27/04 | 04/27/04 | 04/27/04 | 04/28/04 | 04/28/04 | 04/28/04 | 04/28/04 |
|---|---|---|---|---|---|---|---|
| Mixture time (clock) | 10:30 | 1:45 | 4:00 | 10:30 | 11:30 | 1:30 | 3:45 |
| Slump flow, mm (in.) | 500 (19.75) | 660 (26) | 595 (23.5) | 620 (24.25) | 635 (25) | 635 (25) | 650 (25.5) |
| VSI | 0 | 2 | 0 | 0 | 0 | 0.5 | 1 |
| $T_{50}$, seconds | N/A | 0.9 | 1.3 | 1.2 | 1 | 1.2 | 1.1 |
| J-ring, mm (in.) | 475 (18.75) | 635 (25) | 565 (22.25) | 580 (22.75) | 595 (23.5) | 610 (24) | 620 (24.5) |
| Difference, mm (in.) | 25 (1.00) | 25 (1.00) | 30 (1.25) | 40 (1.50) | 40 (1.50) | 25 (1.00) | 25 (1.00) |
| V-funnel, seconds | 1.97 | 1.67 | 2.12 | 2.02 | 1.87 | 1.82 | 1.86 |
| Column segregation ratio | 7 | 10.7 | 4.2 | 5.3 | 7.9 | 9.7 | 8.6 |

**Table 5.3—Statistical data for production SCC**

| | Column segregation, % | V-funnel, seconds | Slump flow, mm (in.) | J-ring difference, mm (in.) |
|---|---|---|---|---|
| Mean | 7.63 | 1.90 | 613 (24.14) | 30 (1.18) |
| Standard deviation | 2.32 | 0.15 | 53 (2.10) | 6 (0.24) |
| Coefficient of variation, % | 30 | 7.9 | 8.7 | 20 |
| Range | 6.50 | 0.45 | 160 (6.25) | 13 (0.50) |
| Minimum | 4.20 | 1.67 | 500 (19.75) | 25 (1.00) |
| Maximum | 10.70 | 2.12 | 660 (26.00) | 25 (1.00) |

**Table 5.4—Cumulative percent passing for fine and coarse aggregate**

| Screen | Fine aggregate | Coarse aggregate |
|---|---|---|
| 12.7 mm (1/2 in.) | 100 | 100 |
| 9.5 mm (3/8 in.) | 100 | 89.6 |
| 4.75 mm (No. 4) | 99.1 | 24.1 |
| 2.36 mm (No. 8) | 79.9 | 8.6 |
| 1.18 mm (No. 16) | 62.8 | 6.1 |
| 0.6 mm (No. 30) | 46.9 | 5.1 |
| 0.3 mm (No. 50) | 19.3 | 4.0 |
| 0.15 mm (No. 100) | 5.3 | 2.7 |
| 0.075 mm (No. 200) | 2.16 | 0.7 |

more fully understand the causes of the difficulties and how best to correct them. Measurements of yield stress and plastic viscosity were made to determine the rheological properties of the trial mixtures. In addition to the measurement of yield stress and plastic viscosity, a shear history plot was developed for several mixtures to characterize any tendency for thixotropy.

SCC is a technology that is growing in use throughout North America. The issue of proportioning SCC mixtures has seen considerable evolution. Therefore, the question arises as to how one can troubleshoot SCC mixtures when the proportioning procedures themselves vary from location to location. This section presents one case history in troubleshooting an SCC mixture for use in precast architectural products.

The precast producer's goal was to have a mixture with a slump flow between 640 to 690 mm (25 to 27 in.) that was stable and could provide a blemish-free architectural surface. In some cases, the producer also wanted to use the mixture for an exposed aggregate finish. Three issues were outlined as the obstacles to incorporating SCC. The first was an inability to obtain an appropriate level of mixture fluidity needed for good surface finish, even though a very high dosage of HRWRA was being used. The elevated dosage of HRWRA caused a significant increase in mixture cost and made SCC uneconomical. The second issue was the inability to maintain a consistent level of mixture stability in the specific mixture being used. During production trials, the instability was noted, qualitatively, as the tendency for the paste to severely separate from the aggregate. The final problem was workability loss experienced during production. The concrete was mixed and then transferred to a transport bucket on a tow motor and delivered to the forms. The degree of workability loss was such that when the discharge door on the bucket was opened, the concrete remained in the bucket. The standard procedure for removing this stiffened concrete from the bucket was to place stinger vibrators into the concrete, which then regained much of its lost workability.

The first two problems were addressed by mixture proportioning adjustments while the other problem was investigated by evaluating the rheological characteristics of the concrete. Because the reported problem included a description of losing fluidity, and subsequently regaining it by imparting vibration, the characteristic of thixotropy was also measured. The remainder of this example outlines the process taken to make mixture adjustments and the resulting performance characteristics of those mixtures.

**5.4.2** *Materials*—Samples of materials were obtained from the producer's plant, including cement (Cement 1) and fly ash as well as both fine and coarse aggregates. Sieve analysis information on the aggregates is presented in Table 5.4. In addition to the customer cement, a laboratory standard ASTM Type I cement (Cement 2) was used in one mixture for comparison purposes.

The admixtures used included a polycarboxylate-based HRWRA, an organic VMA, and a nonchloride accelerator (NCA).

**5.4.3** *Test methods*—All concrete mixtures were prepared in 57 L (2 $ft^3$) batches and mixed in a standard laboratory drum mixer. The batching sequence of the materials was the VMA and NCA added into the initial mixture water followed by the stone, cement, and sand. The final trim water and HRWRA were added last to achieve the target slump flow.

In measuring the fluidity and stability characteristics of the mixtures, the following test procedures were used:

- **Slump flow** (Section 3.3.2.7);
- **$T_{50}$ measurement** (Section 3.3.2.7);
- **Characterization of yield stress, plastic viscosity, and thixotropy**—A commercially available concrete

**Table 5.5—Concrete mixture proportions and performance data**

| Mixture identification | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Cement 1, kg/m$^3$ (lb/yd$^3$) | 417 (703) | 0 (0) | 411 (692) | 427 (720) | 365 (616) |
| Cement 2, kg/m$^3$ (lb/yd$^3$) | 0 | 417 (703) | 0 | 0 | 0 |
| Fly ash, kg/m$^3$ (lb/yd$^3$) | 0 | 0 | 0 | 59 (99) | 117 (198) |
| Coarse aggregate, kg/m$^3$ (lb/yd$^3$) | 996 (1679) | 996 (1679) | 794 (1338) | 790 (1331) | 777 (1309) |
| Fine aggregate, kg/m$^3$ (lb/yd$^3$) | 618 (1041) | 622 (1048) | 800 (1348) | 796 (1342) | 782 (1318) |
| *S/A* | 0.38 | 0.38 | 0.50 | 0.50 | 0.50 |
| Water, kg/m$^3$ (lb/yd$^3$) | 203 (343) | 203 (343) | 201 (338) | 209 (352) | 208 (350) |
| PC HRWRA, mL/100 kg cementitious (oz/100 lb cementitious) initial | 2480 (38) | 1500 (23) | 2020 (31) | 1630 (25) | 1370 (21) |
| PC HRWRA, mL/100 kg cementitious (oz/100 lb cementitious) final | — | — | — | 2150 (33) | 1560 (24) |
| VMA, mL/m$^3$ (oz/yd$^3$) | 75 (2) | 75 (2) | 75 (2) | 75 (2) | 75 (2) |
| NCA, mL/100 kg cementitious (oz/100 lb cementitious) | 980 (15) | 980 (15) | 980 (15) | 980 (15) | 980 (15) |
| Air, % | 2.2 | NA | 5.5 | 1.2 | 1.4 |
| Slump flow, mm (in.) initial | 545 (21.5) | 620 (24.5) | 535 (21) | 545 (21.5) | 560 (22) |
| Slump flow, mm (in.) final | — | — | — | 680 (26.75) | 680 (26.75) |
| $T_{50}$, S initial | 7.5 | 4.2 | 5.4 | 6.9 | 3.5 |
| $T_{50}$, S final | — | — | — | 4.2 | 3.4 |
| VSI, initial | 3 | 3 | 1 | 0 | 0 |
| VSI, final | — | — | — | 1 | 1 |
| 25-minute slump flow, mm (in.) | 200 (8.0) slump | NA | 430 (17) | 635 (25) | 675 (26.5) |
| 25-minute IBB yield stress, Nm | NA | NA | –0.17 | –0.7 | –0.8 |
| 25-minute IBB plastic viscosity, Nms | NA | NA | 8.17 | 7.5 | 5.7 |

rheometer was used to quantify the rheological characteristics of the mixtures (Section 3.3.1.4.11). Because of the phenomena of losing significant workability and then regaining that workability when vibration is applied to the concrete, a special IBB rheometer program was developed for evaluating these mixtures. The program includes the measurement of several points at identical rotation speeds on both the upward and downward portion of the speed loop. The resulting plot shows the shear history of the concrete. Differences in the torque values at the various speeds provide insight into how the concrete's rheological properties are affected by time and energy input. Because thixotropy is time dependent, the concrete was placed in a wheelbarrow with plastic draped over the top and allowed to sit for 25 minutes, then, without remixing, the concrete was scooped from the wheelbarrow into the rheometer and tested. An additional slump flow test was performed at this time as well; and

- **Visual stability index (VSI)** (Section 3.3.2.7).

**5.4.4** *Concrete mixtures*—Table 5.5 contains the mixture proportions tested and the fresh properties measured. The concrete evaluation consisted of running the original SCC mixture that was developed in the field, then making successive adjustments to the mixture proportions to provide the appropriate workability and stability characteristics. In addition to developing an appropriate mixture, the goal was to develop an understanding of why some of the problems were occurring. To accomplish this, on some mixtures, multiple data points were taken, listed in Table 5.5 as initial and final. This indicated that initial measurements were taken, the concrete was placed back into the mixer, more HRWRA was added, and the final measurement was taken.

**5.4.5** *Analysis of concrete mixture proportions*—As Table 5.5 shows, the HRWRA dosage for Mixture 1 (original mixture) was extremely high, even with a substantial water content. The first step in determining the cause and remedy for the elevated HRWRA dosage was to simply examine the effect of cement. When the same mixture was run (Mixture 2) with Cement 2, the HRWRA dosage was decreased by 40% while achieving even higher levels of fluidity. This clearly indicated that the Cement 1 was a significant source of the problems being experienced. Although the HRWRA dosage could be reduced by using an alternate cement, in practice, this would not be an option and the mixture, as designed, was still underperforming. The instability of the mixture can be seen by the VSI ratings of Mixtures 1 and 2 in Table 5.5 as well as a picture of Mixture 1 in Fig. 5.17. Therefore, some adjustments to the overall mixture proportions were necessary.

The aggregate particle-size distribution is known to affect the fresh properties of concrete. In analyzing SCC mixtures, one of the first steps is to review the overall aggregate gradation. The combined aggregate gradation of the original production mixture is presented in Fig. 5.18. As this figure demonstrates, the original mixture proportions incorporated a high amount of 4.75 mm (No. 4) particle size material into the mixture. The results of this aggregate grading are evident in Fig. 5.17. It is evident from this picture that the mixture is very harsh and appears to contain a high volume of coarse aggregate. The total coarse aggregate volume, however, is

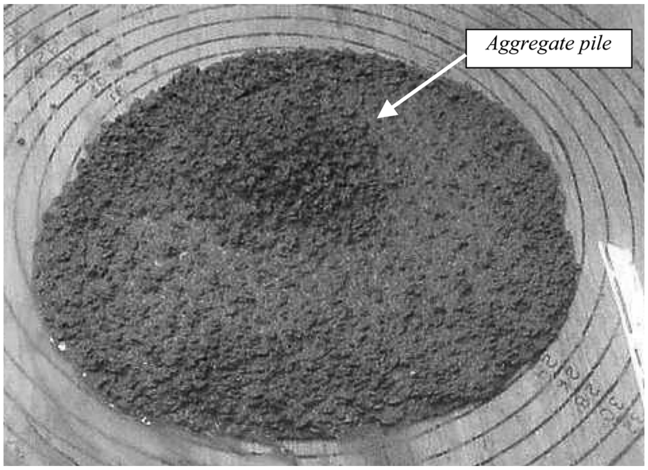



*Fig. 5.17—Mixture 1 with VSI of 3.*

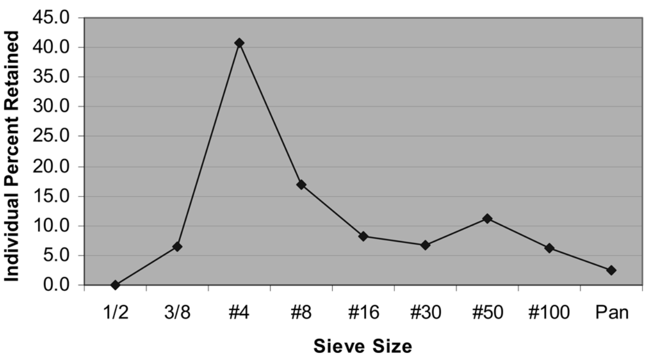



*Fig. 5.18—Aggregate particle-size distribution for Mixture 1.*

*Fig. 5.19—Mixture 3 with VSI of 1.*

not extreme, but because of the particle-size distribution, the volume of 4.75 mm (No. 4) sized particles is. This high volume of a single particle size resulted in particle-to-particle interference, thereby inhibiting flow of the concrete mixture. Based on both the sieve analysis and the results of the mixture, a decrease in the coarse aggregate content was deemed necessary. Mixture 3 was the result of this adjustment. Because the producer wanted to use this mixture for an exposed-aggregate finish, the decrease in coarse aggregate content had to be limited. The adjustment resulted in over 120 kg/m$^3$ (200 lb/yd$^3$) of this 4.75 mm (No. 4) sized material being removed from the mixture, reducing particle-to-particle interference, and allowing for a more flowable mixture. In addition, this adjustment resulted in a lower HRWRA dosage than Mixture 1 and a more stable mixture (VSI 1), as can be seen in Fig. 5.19.

Mixture 3 still did not achieve the desired level of performance. The HRWRA dosage was still fairly high, and the fluidity of the mixture was not at the level needed (slump flow of 640 to 690 mm [25 to 27 in.]) The next adjustment that was made was to raise the total cementitious content by adding fly ash. Mixture 4 added approximately 60 kg/m$^3$ (100 lb/yd$^3$) of fly ash to the mixture, resulting in the ability to achieve a higher level of fluidity while still maintaining good stability (VSI 1). The *S/A* was held constant; therefore, this increase in cementitious content reduced the amount of 4.75 mm (No. 4) sized particles even further because of the need to appropriately yield the concrete mixture.

**5.4.6** *Analysis of rheological behavior and thixotropy*—Mixture 5 added approximately 120 kg/m$^3$ (200 lb/yd$^3$) of fly ash and reduced the cement by 60 kg/m$^3$ (100 lb/yd$^3$). The incorporation of more fly ash and reduction in cement decreased the effect of the cement on the HRWRA dosage and helped to reduce the dosage. In addition, the fly ash promoted a higher fluidity level and further reduced the HRWRA requirement.

The 25-minute slump flow test provided significant insight into the practical issues experienced during the production trials of the original SCC mixtures. After 25 minutes of rest without agitation, Mixture 1 changed from a SCC mixture to a mixture with a slump of 200 mm (8 in.). No rheometer measurements were available for this mixture. As the mixture proportions were adjusted to decrease the coarse aggregate content, the mixture was able to hold its fluidity level slightly better. As more fly ash was added to the mixture, cement reduced and slump flow increased, and the fluidity retention was dramatically improved. On Mixture 5, only 5 mm (0.2 in.) of slump flow was lost after 25 minutes of static rest. In addition, as the changes were made from Mixtures 3 through 5, a reduction in mixture viscosity was observed. This decrease in viscosity would promote a better surface finish on architectural pieces.

Figure 5.20 presents the shear history curves of Mixtures 3 through 5. The area outlined by these flow curves relates to the energy needed to break down the thixotropic structure in the mixtures. The greater the area, the greater the amount of thixotropic structure developed. The area occupied by the curves for the three mixtures is quite different. While slump loss or slump flow loss is typically associated with false set or cement/admixture incompatibility, in this case, the materials used in this mixture tended to produce thixotropic characteristics in the concrete. Because of the smaller amount of slump flow loss and the smaller hysteresis curve when replacing some of the cement in Mixture 4 with more fly ash in Mixture 5, it was concluded that the cement was the main variable causing the thixotropic behavior.

**5.4.7** *Conclusions*—An architectural precast concrete producer was experiencing three basic problems while implementing SCC into production. The three problems, their cause, and solutions are presented as follows.

1. An inability to attain an appropriate level of fluidity even at extremely high HRWRA dosages.

**Cause:** A mixture proportion using a coarse aggregate containing a high volume of 4.75 mm (No. 4) sized particles resulted in particle-to-particle interference and a cement that required high water and HRWRA contents.

**Solution:** The cement source could not be changed, so additional fly ash was used as a cement replacement. The *S/A* was adjusted to reduce particle-to-particle interference.

2. An inability to maintain an appropriate level of mixture stability.

**Cause:** A mixture proportion using a coarse aggregate containing a high volume of 4.75 mm (No. 4) sized particles resulted in particle-to-particle interference that required high water and HRWRA contents, resulting in a highly dispersed paste that could easily exhibit bleeding.

**Solution:** The *S/A* was adjusted to reduce particle-to-particle interference, and thereby reduce HRWRA dosage.

3. A tendency for the mixture to stiffen severely during transport.

**Cause:** The particular cement being used resulted in the development of thixotropic stiffening in the concrete.

**Solution:** The total cementitious content was increased by approximately 60 kg/m$^3$ (100 lb/yd$^3$) and the cement content was reduced by approximately 60 kg/m$^3$ (100 lb/yd$^3$), resulting in a mixture using 25% fly ash. This also allowed for an increase in the slump flow level, further dispersing the cementitious material.

Based on the presented data, the following conclusions can be made:

1. Too much of a single particle size in the aggregate distribution inhibits flow, and can promote instability and increase the HRWRA dosage requirement;

2. Some cements can impart thixotropic properties to a concrete mixture, resulting in workability loss with time; and

3. A concrete rheometer is a useful tool in diagnosing flow retention problems and can quantify behavior experienced in the field.

This example was adapted from Daczko and Kolokithas (2005).

## 5.5—Use of rheological approach to optimize cement-based grout for underwater crack injection of damaged bridge

Repair grout suitable for sealing cracks should be fluid enough to facilitate injectability under relatively low pressure. Low injection pressure is necessary to reduce the risk of crack propagation in rehabilitation work of unconfined concrete. The grout should exhibit sufficient stability to reduce sedimentation, bleeding, and water dilution. Other critical characteristics include the ability of the grout to penetrate fine cracks, its strength and adhesion to repair concrete, its mechanical and thermal compatibility with repair surfaces, and its permeability.

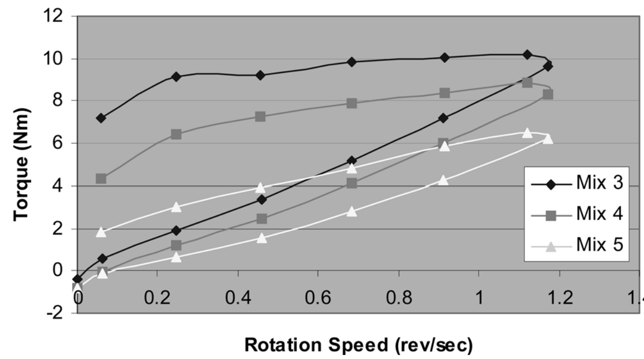



*Fig. 5.20—Shear history plot of torque versus rotation speed.*

Khayat et al. (1997) compared the performance of cement grouts that can be used for crack injection of submerged concrete bridge elements. The investigation included a laboratory study to optimize grout mixture proportions and compare the performance of a selected cement-based grout to that of epoxy resin grout commonly used for the injection grouting of submerged elements. Blended silica fume and microfine cements were used in the laboratory investigation. The resistance to washout of the grouts made with silica-fume cement was further enhanced using welan gum and cellulose-based antiwashout admixtures. The microfine cement had a mean particle diameter of 3.5 μm compared with 14 μm for the blended silica-fume cement. Four optimized grouts were investigated. The microfine cement grout (MF-1) was proportioned with a 0.6 *w/cm*. The Control, AWA-1, and AWA-2 were proportioned without antiwashout admixture (AWA), with welan gum, and with cellulose AWA, respectively, and were prepared with blended silica-fume cement and a 0.45 *w/cm*. As shown in Fig. 5.21, the MF-1 grout exhibited considerably lower viscosity at low and high shear rates than the other grouts made with silica-fume cement. The optimized grouts in Fig. 5.21 had relatively low apparent viscosities at high shear rates that dominate during mixing and pumping operations. Unlike the other mixtures, the MF-1 grout maintained low viscosity at low shear rates, which were predominant at the end of grouting when the grout can further flow into place by gravity and capillary action.

The use of a modified Marsh cone did not provide enough sensitivity in detecting the variations in fluidity between the Control and MF-1 grouts at high shear rates. On the other hand, the measurement of flow time was more sensitive in detecting variations in fluidity between the AWA-1 and AWA-2 mixtures, which exhibited similar mini-slump values. A coaxial cylinder viscometer was used to evaluate rheological properties of cement grout. The apparent viscosity μ was determined on 350 mL (11.8 oz) samples of grout at 11 rotation speeds corresponding to shear rates of 1.7 to 1020 s$^{-1}$.

The MF-1 grout also presented high resistance to washout and the highest fluidity, as indicated in Fig. 5.22. The washout mass loss was evaluated using a 500 mL (11.8 oz) grout sample poured into a beaker of an equivalent volume containing water. The washout mass loss was determined by

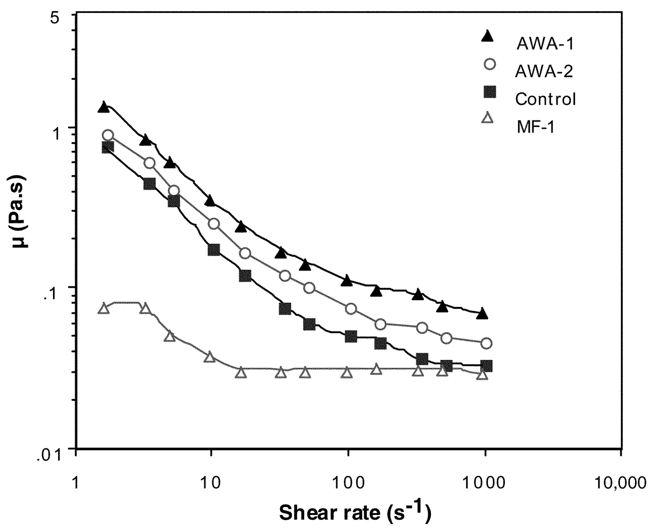



*Fig. 5.21—Pseudo-plastic behavior of four optimized grout mixtures. MF-1 grout was selected for pier repairs given its relatively low shear-thinning response.*

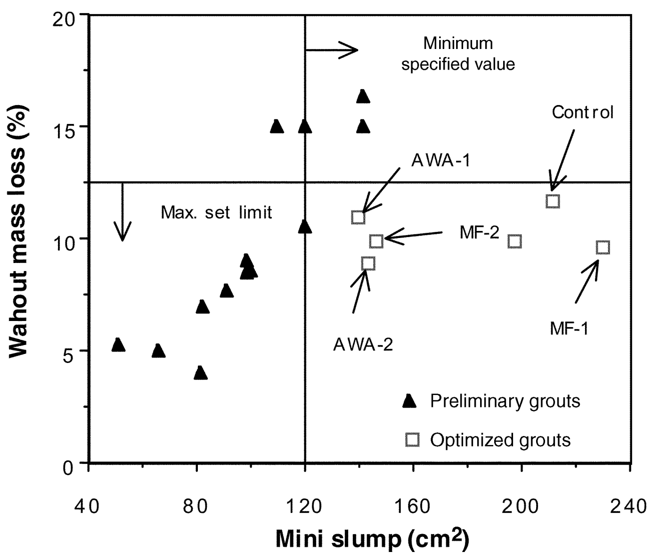



*Fig. 5.22—Variations of washout mass loss of cement grout with mini slump flow. MF-1 grout selected for underwater pier repair exhibits the best combined flow-stability response.*

measuring the difference in mass of the grout before and after freefall in water (Khayat and Yahia 1996).

Based on the rheological characteristics of the investigated grout mixtures and their set time and strength development properties, the MF-1 grout was selected for the field investigation. The MF-1 grout was found to be robust as it exhibited limited sensitivity in rheological parameters, flow and washout characteristics, set time, and development of compressive strength when small changes in *w/c*, HRWRA dosage, and material temperature were made.

The optimized MF-1 grout was used to repair two bridge pier shafts and footings. The majority of surface crack widths were between 2 and 10 mm (0.08 and 0.4 in.) at the surface; however, crack widths were significantly reduced beyond the outer 300 mm (12 in.) from the surface. The cement grout was mixed and tested on a working barge floating near the bridge pier shafts that were repaired. The cement-based grout was sampled to determine unit weight, fluidity using the mini slump and modified Marsh cone tests, and washout mass loss. Such quality-control tests were easy to set up on a barge, and simple and quick to perform; hence, they did not interfere with the grouting operation. Rheological properties were also determined using a coaxial viscometer.

Core samples taken from repair pier elements showed that the selected grout developed bond strength to submerged concrete that was similar to that of a high-quality epoxy resin used also for underwater injection grouting of two pier shafts and footings. The relatively low viscosity of the MF-1 grout compared with that of epoxy resin resulted in lower requirement of injection pressure. Despite the lower injection pressure, the grout intake was reported to be 2.8 times greater per linear meter of surface crack than that observed for the epoxy resin grout. The mean volumes of injected cement-based and epoxy resin grouts per linear meter of surface crack were approximately 2.08 and 0.73 L/m (0.17 and 0.06 gal./ft), respectively. The greater injectablity of the microfine cement grout reflects greater intake and higher penetrability of the low-viscosity grout with fine cement grains compared with the more viscous epoxy resin grout. The low viscosity of the cement-based grout also led to faster grout placement where the mean injection volumes per hour of the epoxy resin and microfine cement grouts were approximately 10 and 50 L/h (2.6 and 13 gal/h), respectively.

Sonic tomography was used to reconstitute the spatial distribution of stress wave velocities within the massive pier footings. These measurements indicated that the quality of concrete was significantly improved following injection with cement-based grout. This improvement was attributed to the high penetrability of the microfine cement grout.

# CHAPTER 6—REFERENCES

## 6.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.


*American Concrete Institute*

211.3R Guide for Selecting Proportions for No-Slump Concrete

309.1R Behavior of Fresh Concrete During Vibration

544.2R Measurement of Properties of Fiber-Reinforced Concrete

*ASTM International*

C29/C29M Test Method for Bulk Density (Unit Weight) and Voids in Aggregate

C124 Method of Test for Flow of Portland-Cement Concrete by Use of the Flow Table (withdrawn)

C143/C143M Test Method for Slump of Hydraulic-Cement Concrete

| | |
|---|---|
| C150 | Specification for Portland Cement |
| C185 | Test Method for Air Content of Hydraulic Cement Mortar |
| C187 | Test Method for Normal Consistency of Hydraulic Cement |
| C191 | Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle |
| C230/C230M | Specification for Flow Table for Use in Tests of Hydraulic Cement |
| C360 | Test Method for Ball Penetration in Freshly Mixed Hydraulic Cement Concrete (withdrawn) |
| C403/C403M | Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance |
| C494/C494M | Specification for Chemical Admixtures for Concrete |
| C939 | Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method) |
| C953 | Test Method for Time of Setting of Grouts for Preplaced-Aggregate Concrete in the Laboratory |
| C995 | Test Method for Time of Flow of Fiber-Reinforced Concrete Through Inverted Slump Cone |
| C1157 | Performance Specification for Hydraulic Cement |
| C1170 | Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table |
| C1362 | Standard Test Method for Flow of Freshly Mixed Hydraulic Cement Concrete |
| C1610/C1610M | Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique |
| C1611/C1611M | Test Method for Slump Flow of Self-Consolidating Concrete |
| C1621/C1621M | Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring |
| D698 | Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft$^3$ (600 kN-m/m$^3$)) |
| D1557 | Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$)) |
| D2573 | Test Method for Field Vane Shear Test in Cohesive Soil |

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# Report on Measurements of Workability and Rheology of Fresh Concrete