

Report on Behavior of Fresh Concrete During Vibration

Reported by ACI Committee 309



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This report covers the rheological and mechanical processes that take place during consolidation of fresh concrete. The first chapter presents the historical developments relative to consolidating concrete. The second chapter provides notations and definitions. The third chapter deals with the rheological behavior of concrete during consolidation and the associated mechanisms of dynamic compaction. The fourth chapter presents the principles of vibratory motion occurring during vibration, vibratory methods, and experimental test results. Continuing research in the field of concrete vibration, as evidenced by the extensive literature devoted to the subject, is addressed.

Keywords: admixtures; aggregates; aggregate shape and texture; aggregate size; amplitude; compacting; consolidation; damping; energy; fresh concrete; hardening; history; mechanical impedance; mixture proportioning; reviews; rheological properties; stability; vibrations; vibrators (machinery).

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CHAPTER 1—INTRODUCTION AND SCOPE

At the turn of the twentieth century, concrete was generally placed as very dry mixtures, and was deposited in thin lifts and rammed into place by heavy tampers, which involved extensive manual labor. Typical structures, such as foundations, retaining walls, and dams, contained little or no reinforcement. The concept of rammed concrete in thin lifts can be traced back to the early Roman times, when the Pantheon was built. Many of these structures are still in service, proving that this type of construction produced strong, durable concrete.

In the early twentieth century, the common use of reinforcing steel in concrete changed the consolidation requirements for concrete. Concrete sections were greatly reduced in thickness. Constructors found that the dry mixtures could not be tamped in the narrow forms filled with reinforcing steel and, consequently, water was added to facilitate placement into forms without regard to effects on the mixture itself. The change from massive tamped concrete structures in the early 1900s to relatively thin, reinforced concrete structures was a major advance in engineering practice, but did not necessarily result in immediate improvements in concrete quality. The dry, tamped concrete structures were somewhat less permeable than the wet concrete placed into the first reinforced structures. Methods other than tamping were tried to consolidate stiffer concrete. Compressed air was introduced into the fresh concrete through long jets. The practice of chuting concrete into place resulted in excessively wet mixtures as the water content was increased (without increasing the cement) to allow the mixture to flow in chutes (Walter 1929). It became apparent that these wet mixtures did not produce good concrete (Engineering News Record 1923). The result was lower strength, durability failures, and increased drying shrinkage and cracking. The poor durability of these first reinforced concrete structures was of great concern to early practitioners. These mixtures would be described as “wetter,” though the slump test was yet to be standardized.

The water-cement ratio concept, postulated by Abrams around 1920, demonstrated that the quality of concrete dropped rapidly as more water was added to the mixture (Abrams 1922a). In addition, the development of the traditional slump test around 1922 gave the first measurable parameter for indicating concrete consistency suitable for placement and an indication of quality (Abrams 1922b). Abrams documented an increase in compressive strength by compacting low-consistency concrete with mechanical jiggling.

Difficulty consolidating concrete in reinforced and mass concrete structures continued to be a problem until the introduction of internal concrete vibrators in the early 1930s (McCarty 1933). The use of vibrators allowed stiffer mixtures with less water to be placed, increasing both concrete strength and durability and decreasing shrinkage. In mass concrete dams, the introduction of the vibrator allowed the placement of very stiff concrete in thick lifts with lower water contents and subsequently less cement, which reduced thermal cracking in dams. Consolidation by internal vibration increased the rate of placement per day, and reduced internal flaws, such as cold joints.

ACI Committee 609 (1936) described the benefits of vibrators but was not able to explain the interaction between a vibrator and fresh concrete. The frequencies of the early 1900s vibrators were limited to 3000 to 5000 vibrations per minute (50 to 80 Hz) because of design and maintenance problems. When it became apparent that higher frequencies were possible and more effective in consolidating concrete, vibrator manufacturers made the necessary improvements.

The following is an historical listing of notable research on the consolidation of fresh concrete. Observations were made on the effect of air entrainment introduced in the late 1940s on concrete consolidation. Air entrainment makes the mixture more cohesive, and enhances particularly lean mixtures deficient in fines, as well as mass concrete.

L'Hermite and Tournon (1948) reported fundamental research on the mechanism of consolidation. They found that friction between the individual particles is the most important factor in preventing consolidation (densification), but friction is practically eliminated when concrete is in a state of vibration.

Meissner (1953) summarized research and reviewed state-of-the-art equipment and its characteristics.

ACI Committee 609 (1960) stated recommendations for vibrator characteristics applicable to different types of construction and described field practices.

Walz (1960) described the various types of vibrators—internal, surface, form, and table—and their application. It was shown that the reduction in internal friction is primarily the result of acceleration produced during vibration.

Rebut (1962) discussed the theory of vibration, including the forces involved, the types of vibrators and their application to different classes of construction, and vibration-measuring devices.

Ersoy (1962) published the results of extensive laboratory investigations on the consolidation effect of internal vibrators. Ersoy varied the concrete consistency, size and shape of form, and vibration parameters and concluded that the eccentric moment, defined as the mass of the eccentric times its eccentricity (distance between the center of gravity and the center of motion), and frequency are important factors for determining the consolidation effectiveness of an internal vibrator.

Kolek (1963) described vibration theories, formulas, and experimental work aimed at a better understanding of the processes involved. He determined that consolidation occurred in two stages: the first stage comprised the major subsidence or slumping of the concrete, and the second stage involved deaeration (removal of entrapped air).

Kirkham (1963) developed empirical formulas to explain the compaction of concrete slabs by the use of vibrating beams or screeds on the surface. The force, amplitude of vibration, and the vibration frequency were found to be the most important factors affecting the degree of consolidation.

Murphy (1964) published a summary of post-World War II British research, and compared the findings and claims of the different investigators. The studies made by Cusens (1955, 1956), Kirkham (1963), and Kolek (1963) on the subject of consolidation were particularly noteworthy.

Forssblad (1965a) reported on measurements of the field of action of internal vibrators operating at different frequencies.

and amplitudes, and with different vibration times and mixture consistencies. The radius of action was determined from photographs of the concrete surface.

Reading (1967) observed that for most ordinary mixtures, the stickiness imparted by air entrainment makes it difficult to release entrapped air; consequently, more vibration may be necessary for certain mixtures. Ritchie (1968) reviewed such concepts as workability and described such factors as stability, compactability, and mobility and the corresponding methods of measurements.

Shtaerman (1970) reported that ultra-high-frequency vibration increases the hydration of the cement and improves the properties of concrete. High energy input and heat generation, and the small depth of penetration of the vibration, however, are drawbacks to this method.

Wilde (1970) discussed the basic parameters involved in the vibrator-concrete interaction and presented formulas for computing the radius and volume affected and the time required for consolidation.

ACI Committee 309 (1982) published a report that explained the basic principles of consolidation and gave recommendations for proportioning concrete mixtures, equipment, and procedures for different types of construction, quality control, vibrator maintenance, and consolidation of test specimens.

A RILEM symposium at the University of Leeds in 1973 included papers by Smalley and Ahmad (1973), Bache (1973), and Popovics (1973) that addressed rheological properties and consolidation of concrete.

Cannon (1974) reported on the compaction of zero-slump concrete with a vibratory roller. Later, ACI Committee 207 (1980) prepared a state-of-the-art report on this subject.

Tattersall (1976) reported on the mobility of concrete by determining power requirements for mixing at various speeds.

Taylor (1976) published the results of extensive laboratory tests on the effect of different parameters on the effectiveness of internal vibrators. Gamma ray scanning was used to determine the density of the concrete and, hence, the radius of action of the vibrators. Acceleration and amplitude were found to be the most important parameters.

Alexander (1977) reported basic research on the mechanics of motion of fresh concrete. It was found that the response of concrete to vibration under low applied forces can be expressed in terms of stiffness, damping, and mass. During vibration, stiffness and damping practically disappear, and only mass is involved.

Tuthill (1977) summarized knowledge of the effects of revibration. Revibration may produce benefits, particularly for the wetter mixtures, by eliminating water that collects under reinforcing bars and reducing bugholes, especially in the upper portion of deep lifts, which increases the strength of the concrete.

Winn et al. (1984) reported on the use of accelerometers to measure the effect of various concrete mixture and vibrator parameters on consolidation of continuously reinforced concrete pavements.

An International Symposium on Concrete Consolidation was sponsored by ACI Committee 309 and presented in

1986 in San Francisco. Papers relating to the behavior of fresh concrete during vibration included the following:

- Forssblad (1987) reported on the need for consolidation of flowing concrete mixtures and how these mixtures responded to internal, surface, and form vibration;
- Harrell and Goswick (1987) reported on the concurrent use of internal and external vibration to obtain superior consolidation in tunnel concrete;
- Kagaya et al. (1987) studied the variations in the contents of the mixture constituents and some of the mechanical properties at various heights of placement within both lightweight and normalweight concrete. They concluded that these variations had a linear correlation with variations in the coarse aggregate content. Furthermore, they showed that when variations in the coarse aggregate content are expressed relative to the coarse aggregate content of a reference mixture, the optimum vibration time can be established for a given placement height for the mixture being evaluated;
- Olsen (1987) used accelerometers to measure the rate of movement of fresh concrete, and was able to establish the minimum energy level required to achieve 97% consolidation or more; and
- Iida and Horigome (1987) reported that better compaction properties of no-slump lean concrete can be obtained by dividing the mixing water into two portions and adding it to the mixture at two different times.

It is apparent that enough has been learned about concrete vibration during the past 50 years to ensure that low-slump concrete can be placed successfully. A better understanding of the interaction of vibration and fresh concrete, however, is still desirable.

In the 1980s, the methods used to place and consolidate many concretes began to change away from the traditional internal or form vibrators. Roller-compacted concrete (RCC) began to be used as a method for rapidly placing no-slump mass concrete with compaction by smooth-drum, vibrating rollers common to embankment construction. The increase in consolidation production per unit equipment went from about 300 yd³ (230 m³) per shift to 3000 yd³ (2295 m³) per shift in mass applications (Dolen 2002). RCC construction diverged in the 1980s into two different methodologies: a concrete approach and a soils approach. The concrete approach followed a more traditional mass concrete technology; the consistency of the concrete was measured by the modified Vebe time, which replaced the slump test. A Vebe consistency of about 20 seconds, according to ASTM C1170, became common for mass dam applications where the RCC was placed in about 1 ft (300 mm) thick lifts. RCC pavements and embankment dam overtopping applications took the soils approach by using the modified Proctor test to place the concrete at optimum moisture content suitable for maximum dry density in about 6 to 9 in. (150 to 225 mm) thick lifts (Ragan 1988).

The introduction of high-range water-reducing admixtures led to the development of very-high-slump concretes that require little internal consolidation. This development was spurred on by the greater reinforcement steel densities necessary

for seismic resistance, nuclear power plant construction, and the more complex structures in bridge and other structural concrete applications. Also, the ever-increasing use of pumped concrete fueled the use of higher-slump concrete with smaller nominal maximum-size aggregates. Difficulties with segregation and extreme bleeding were encountered with these early high-slump mixtures, leading to the introduction of new mid-range and high-range water-reducing admixtures, and, more recently, viscosity-modifying admixtures (VMAs) in the 1990s. Again, the traditional slump test could no longer adequately describe the consistency of these new high-performance (HPC) and self-consolidating (SCC) concretes. ACI 237R defines self-consolidating concrete as highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. In general, SCC is concrete made with conventional concrete materials and, in some cases, with a VMA. SCC has also been described as self-compacting concrete, self-placing concrete, and self-leveling concrete, which all are subsets of SCC.

The flow table, J-ring and L-box tests described in Table 2.1 of ACI 237R are used to evaluate concrete consistency suitable for SCC. Chan et al. (2003) reported the effects of vibration and overvibration on the consolidation and bond of reinforcement for normal-slump concrete, HPC, and SCC. They concluded that vibration is essential for development of bond reinforcement for normal concrete, some limited vibration is necessary for HPC, and that SCC should not be vibrated. In some cases, concrete that has a high slump flow, such as SCC, cannot flow satisfactorily to obtain a good consolidation, and intervention by a mechanical device (vibration or tamping) might be necessary. This concrete is not considered SCC, but is considered normal concrete with a high slump flow.

Although the aforementioned developments in placing concretes have replaced the more traditional, specified use of internal vibration, the tried and true methodology for consolidating mass and conventional structural concretes has not been eliminated. The ever-increasing use of grout-enriched roller-compacted concrete (GERCC) has brought the large-size internal vibrators back to the mass concrete dams as a better means of increasing consolidation at the upstream and downstream faces of RCC dams (Forbes et al. 1999). Highway pavements, canal linings, and precasting construction continue to require the effective use of both internal and form vibrators to achieve consolidation. The fundamental properties of internal vibration and consolidation are described in the following chapters.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a	=	acceleration, ft/s ² (m/s ²)
c	=	wave velocity, ft/s (m/s)
c_1	=	constant, depending on stiffness and damping in the concrete
E	=	dynamic modulus of elasticity, lb/ft ² (MPa)
F	=	force, lbf (N)
f	=	frequency, Hz
g	=	acceleration due to gravity, in./s ² (mm/s ²)

h	=	depth below surface, ft (m)
m	=	concrete mass, lb/(32.2 ft/s ²) (kg/[9.81 m/s ²])
m_e	=	weight of eccentric, lb (kg)
m_v	=	vibrator weight minus the eccentric weight, lb (kg)
m_b	=	weight of displaced concrete, lb (kg)
r	=	eccentricity of the eccentric weight, in (mm)
s	=	amplitude, in. (mm)
s_x	=	amplitude at distance x from a reference point, in. (mm)
t	=	time, s
v	=	maximum particle velocity, ft/s (m/s)
γ	=	density, lb/ft ³ (kg/m ³)
$\dot{\gamma}$	=	linear relationship between shear stress and shear rate of concrete
η_{pl}	=	plastic viscosity of concrete
σ	=	shear stress of concrete
σ_B	=	Bingham yield stress of concrete
ω	=	angular velocity, radian/s
Ω	=	coefficient of damping

2.2—Definitions

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—(1) the consistency at which a mixture subjected to a constant stress undergoes increasing deformation without rupture; or (2) the consistency at which mixture properties satisfy appropriate limits defined in a standard test method.

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 measurement in which consistency is reported in degrees of rotation of a torque viscometer in a specimen of grout.

consolidation—the process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar, during placement by the reduction of voids; usually by vibration, centrifugation, rodding, tamping, or some combination of these actions; also applicable to similar manipulation of other cementitious mixtures, soils, aggregates, or the like.

Note: In Europe, the word “compaction” is used instead of consolidation, but the term “compaction” in the U.S. is related to soil and not to concrete, except for roller-compacted concrete (RCC). The British Standard BS 1881-103 (British Standards Institute 1993) covers the definition and measurement of the compaction factor. Although the test has a wide range of applications, it has some limitations.

finishing—leveling, smoothing, consolidating, and otherwise treating the surfaces of fresh or recently placed concrete or mortar to produce the desired appearance and service.

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

mobility—the ability of fresh concrete or mortar to flow.

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

workability (placeability)—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.

CHAPTER 3—INFLUENCE OF RHEOLOGY ON CONSOLIDATION OF FRESH CONCRETE

3.1—Rheology of fresh concrete

Rheology is the science of deformation and flow of matter (Hackley and Ferraris 2001). Therefore, rheological properties of concrete are especially relevant for handling and placing of freshly mixed concrete, and the behavior of slurries and pastes.

In a concrete project, it is usually desirable to produce the highest practical and economical density, that is, with a minimum of entrapped voids. To achieve this goal, it is necessary to compare the vibrator characteristics with those of the concrete mixture. This requires a thorough understanding of the properties of fresh concrete under vibration. Studies on the rheology of fresh concrete attempted to define the parameters involved (Lassalle and Legrand 1980; Kitaoji et al. 1998; Banfill et al. 1999; Safawi et al. 2005). In this chapter, these parameters are reviewed on the basis of recent research and from the standpoint of application to the consolidation of fresh concrete.

Current standard test methods for determining concrete workability yield results of limited scope because they measure only one parameter. Examples of these tests are the slump, compacting factor, Vebe consistency, and other remolding and deforming tests (Ferraris 1996; Hackley and Ferraris 2001; ACI 238.1R). Results of these tests and their interpretations as well as the rheology of fresh concrete are discussed by Popovics (1982), Ferraris (1996), and Koehler and Fowler (2003). It is generally accepted that the rheological properties of concrete are complex and need to be defined by several parameters and tests. The selection of the tests depends on the flow properties required for the application as well as the devices available. Most researchers agree that concrete flows could be described by the Bingham model (Bingham and Reiner 1933). This model shown in Fig. 3.1 can be described by Eq. (3-1)

$$\begin{aligned}\sigma &= \sigma_B + \eta_{pl}\dot{\gamma} \\ \dot{\gamma} &= 0 \text{ for } \sigma < \sigma_B\end{aligned}\quad (3-1)$$

The Bingham relation is a two-parameter model used for describing viscoplastic fluids that exhibit a yield response.

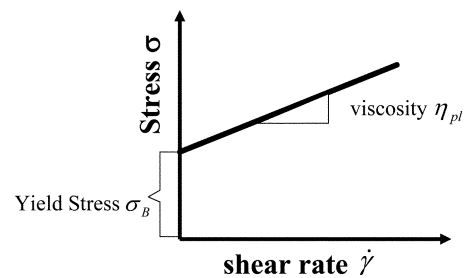


Fig. 3.1—Bingham model.

The ideal Bingham material is an elastic solid at low shear stress values σ , and a Newtonian fluid above a critical value called the Bingham yield stress σ_B . The plastic viscosity region, with a shear stress above the yield stress, exhibits a linear relationship between shear stress and shear rate $\dot{\gamma}$, with a constant differential viscosity equal to the plastic viscosity η_{pl} . The yield stress is correlated with the slump cone test (Ferraris and de Larrard 1998), whereas the plastic viscosity can only be measured using a rotational rheometer.

Several tests and studies were conducted to determine the proper methodology to measure the Bingham parameters for concrete and the device to be used. Two international round-robin tests were conducted (Ferraris and Brower 2001, 2004). A description of other rheometers is included in Koehler and Fowler (2003) and in ACI 238.1R.

A property that is related to the rheological behavior of the concrete or its constituents, cement paste, or mortar, is stability (ACI 237R). Stability of concrete describes the ability of a material to maintain homogeneous distribution of various constituents during its flow and setting. There are two types of stability characteristics that are important: dynamic and static stability.

Dynamic stability refers to the resistance of concrete to separation of constituents upon placement and spread into the formwork. Adequate dynamic stability is required when the application has requirements such as flowing through closely spaced obstacles and narrow spaces or transport of concrete without agitation.

Static stability refers to the resistance of concrete to bleeding, segregation, and surface settlement after casting while the concrete is still in a plastic state. In special cases, induced loss of water or controlled bleeding may be desirable but, as a rule, bleeding should be controlled and reduced to a minimum. Segregation (ACI 237R) is described as the instability of a concrete mixture caused by a low yield and low-viscosity matrix resulting in individual aggregates to not maintain homogeneous dispersion. When concrete is vibrated, the matrix regains fluid behavior and exhibits a measurable shear resistance and cohesion. In this report, the concern is consolidation of concrete by achieving the highest density, that is, a reduction of voids. This can be achieved by mechanical energy (vibration or tamping) or by the concrete flow under its own weight (for instance, SCC).

Ritchie (1968) extended the compacting factor test by taking two additional measurements. One was the density of concrete in its loose, unconsolidated state. This state