Guide for Consolidation of Concrete

Reported by ACI Committee 309

Richard E. Miller
Chair

Jerome H. Ford
Subcommittee Chair

Neil A. Cumming
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Chiara F. Ferraris
Steven H. Gebler
Glenn A. Heimbruch

Kenneth C. Hover
Garry R. Mass
Bryant Mather*
Larry D. Olson

H. Celik Ozyildirim
Steven A. Ragan
Mike Thompson
Bradley K. Violetta

*Deceased.

Consolidation is the process of removing entrapped air from freshly placed concrete. Several methods and techniques are available, the choice depending mainly on the workability of the mixture, placing conditions, and degree of air removal desired. Some form of vibration is usually employed.

This guide includes information on the mechanism of consolidation and gives recommendations on equipment, characteristics, and procedures for various classes of construction.

The paired values stated in inch-pound units and hard SI units are usually not exact equivalents. Therefore, each system is to be used independently of the other. Combining values from the two systems may result in nonconformance with this guide.

Keywords: box out; compaction; consistency; consolidation; placing, rheology; rodding; segregation; spading; tamping; vibration; vibrator; workability.

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ACI 309R-05 became effective August 5, 2005 and supersedes ACI 309R-96.

CHAPTER 1—GENERAL

Freshly placed unconsolidated concrete contains excessive and detrimental entrapped air. If allowed to harden in this condition, the concrete will be porous and poorly bonded to the reinforcement. It will have low strength, high permeability, and poor resistance to deterioration. It may also have a poor appearance. The mixture should be consolidated if it is to have the properties desired and expected of concrete.

Consolidation is 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 (spinning), rodding, spading, tamping, or some combination of these actions.

Stiffer mixtures require greater effort to achieve proper consolidation. By using certain chemical admixtures (ACI 212.3R), consistencies requiring reduced consolidation effort can be achieved at lower water content. As the water content of the concrete is reduced, concrete strength, permeability, and other desirable properties improve, provided that the concrete is properly consolidated. Alternatively, the

Fig. 1.1(a)—Pleasing appearance of concrete in church construction.

Fig. 1.1(b)—Pleasing appearance of concrete in utility building construction.

Fig. 1.1(c)—Close-ups of surfaces resulting from good consolidation.

cementitious materials content can be lowered, reducing the cost while maintaining the same strength. If adequate consolidation is not provided for these stiffer mixtures, the strength of the in-place concrete decreases rapidly.

Equipment and methods are now available for fast and efficient consolidation of concrete over a wide range of placing conditions. Concrete with a relatively low water content can be readily molded into an unlimited variety of shapes, making it a highly versatile and economical construction material. When good consolidation practices are combined with good formwork and good form release agents, concrete surfaces have a highly pleasing appearance (Fig. 1.1(a) through (c)).

CHAPTER 2—EFFECT OF MIXTURE PROPORTIONS ON CONSOLIDATION

2.1—Mixture proportions

Concrete mixtures are proportioned to provide the workability needed during construction and the required properties in the hardened concrete. Mixture proportioning is described in ACI 211.1, 211.2, and 211.3R.

2.2—Workability and consistency

Workability of freshly mixed concrete determines the ease and homogeneity with which concrete can be mixed, placed,

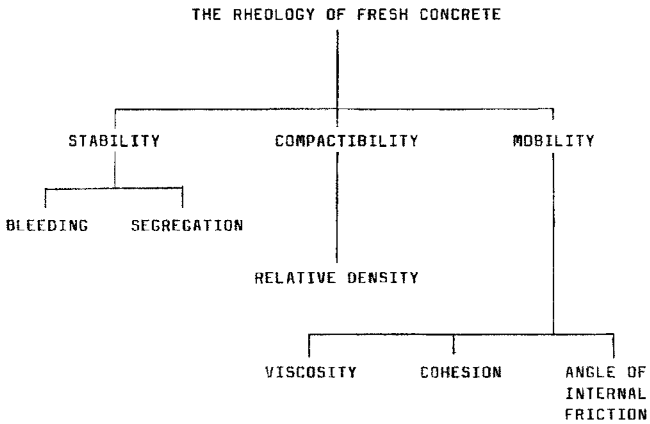

Fig. 2.1—Parameters of rheology of fresh concrete.

Table 2.1—Consistencies used in construction*

Consistency description	Slump, in. (mm)	Vebe time, s	Compacting factor average	Thaulow drop table revolutions
Extremely dry	—	32 to 18	—	112 to 56
Very stiff	—	18 to 10	0.70	56 to 28
Stiff	0 to 1 (0 to 25)	10 to 5	0.75	28 to 14
Stiff plastic	1 to 3 (25 to 75)	5 to 3	0.85	14 to 7
Plastic	3 to 5 (75 to 125)	3 to 0*	0.90	<7
Highly plastic	5 to 7-1/2 (125 to 190)	—	—	—
Flowing	7-1/2 plus (190 plus)	—	0.95	—

*Test method is of limited value in this range.

consolidated, and finished. Workability is a function of the rheological properties of the concrete.

As shown in Fig. 2.1, workability may be divided into three main aspects:

1. Stability (resistance to bleeding and segregation);
2. Ease of consolidation; and
3. Consistency, affected by the viscosity and cohesion of the concrete and angle of internal friction.

Workability is affected by grading, particle shape, surface texture, proportions of aggregate and cement, use of pozzolan or ground-granulated blast-furnace slag (GGBFS), chemical admixtures, air content, and water content of the mixture. Consistency is the relative mobility or ability of freshly mixed concrete to flow. It also largely determines the ease with which concrete can be consolidated. Once the materials and proportions are selected, the primary control over workability is through variations in the water content or by adding a chemical admixture. The slump test (ASTM C 143) is widely used to indicate consistency of mixtures used in normal construction. The Vebe test (ASTM C 1170) is recommended for stiffer mixtures. Values of slump, compacting factor, drop table spread, and Vebe time for the entire range of consistencies used in construction are given in Table 2.1.

Other measures of consistency, such as the Powers' remolding test and the concrete rheometers recently developed, are available. These methods are infrequently used. The various consistency tests have been discussed by Neville (1981), Vollick (1966), and Ferraris (1999).

2.3—Workability requirements

The concrete should be sufficiently workable so that consolidation equipment, when properly used, will give adequate consolidation. A high degree of ability to flow may be undesirable because it may increase the cost of the mixture and reduce the quality of the hardened concrete. Where such a high degree of ability to flow is the result of too much water in the mixture, the mixture will generally be unstable and will probably segregate during the consolidation process.

In mixtures that are highly plastic to flowing (Table 2.1), small nominal maximum-size aggregate and high content of fine aggregate are frequently used because the high degree of ability to flow means less work in placing. Mixtures such as these may have undesirable characteristics such as high shrinkage, cracking, and stickiness. At the other extreme, it is inadvisable to use mixtures that are too stiff for the intended conditions of consolidation. They will require great consolidation effort and even then may not be adequately consolidated. Direction, guidance, and trail mixtures are often required to achieve the use of mixtures of lower slump or fine aggregate content, or a larger nominal maximum-size aggregate, so as to give a more efficient use of the cement.

Concrete containing certain chemical admixtures may be placed in forms with less consolidation effort. Refer to reports of ACI Committee 212 for additional information. The use of pozzolans or GGBFS may also affect the consolidation effort required to properly consolidate concrete. Refer to ACI 232.2R, 233R, and 234R for more information regarding these materials. The amount of consolidation effort required with or without the use of chemical admixtures and pozzolans or GGBFS should be determined by trial mixtures under field conditions.

The workability of the mixture in the form determines the consolidation requirements. This workability may be considerably less than at the mixer because of slump loss due to high temperature, premature stiffening, delays, or other causes.

CHAPTER 3—METHODS OF CONSOLIDATION

The consolidation method should be compatible with the concrete mixture, placing conditions, form intricacy, and amount of reinforcement. Many manual and mechanical methods are available.

3.1—Manual methods

Plastic, highly plastic, and flowing consistency (Table 2.1) mixtures may be consolidated by rodding. Spading is sometimes used at formed surfaces—a flat tool is repeatedly inserted and withdrawn adjacent to the form. Coarse particles are shoved away from the form and movement of air voids toward the top surface is facilitated, thereby reducing the number and size of bugholes in the formed concrete surface.

Hand tamping may be used to consolidate stiff mixtures. The concrete is placed in thin layers, and each layer is carefully rammed or tamped. This is an effective consolidation method but is laborious and costly.

The manual consolidation methods are generally only used on smaller nonstructural concrete placements and are labor intensive.

3.2—Mechanical methods

The most widely used consolidation method is vibration. Vibration may be either internal, external, or both.

Power tampers may be used to compact stiff concrete in precast units. In addition to the ramming or tamping effect, there is a low-frequency vibration that aids in the consolidation. Mechanically operated tamping bars are suitable for consolidating stiff mixtures for some precast products, including concrete masonry units.

Equipment that applies static pressures to the top surface may be used to consolidate thin concrete slabs of plastic or flowing consistency. Concrete is literally squeezed into the mold, and entrapped air and part of the mixing water is forced out.

Centrifugation (spinning) is used to consolidate concrete in concrete pipe and other hollow sections and piles and poles.

Many types of surface vibrators are available for slab construction, including vibrating screeds, vibratory roller screeds, plate and grid vibratory tampers, and vibratory finishing tools.

Shock tables, sometimes called drop tables, are suitable for consolidating low-slump concrete. The concrete is deposited in thin lifts in sturdy molds. As the mold is filled, it is alternately raised a short distance and dropped on to a solid base. The impact causes the concrete to be rammed into a dense mass. Frequencies are 150 to 250 drops per min, and the free fall is 1/8 to 1/2 in. (3 to 13 mm).

Smooth-drum vibratory rollers are commonly used to consolidate no-slump concrete mixtures.

3.3—Methods used in combination

Under some conditions, a combination of two or more consolidation methods gives the best results.

Internal and external vibration can often be combined to advantage in precast work and occasionally in cast-in-place concrete. One scheme uses form vibrators for routine consolidation and internal vibrators for spot use at critical, heavily reinforced sections prone to voids or poor bond with the reinforcement. Conversely, in sections where the primary consolidation is by internal vibrators, form vibration may also be applied to achieve the desired surface appearance.

Vibration may be simultaneously applied to the form and the top surface. This procedure is frequently used in making precast units on vibrating tables. The mold is vibrated while a vibratory plate or screed working on the top surface exerts additional vibratory impulses and pressure.

Vibration of the form is sometimes combined with static pressure applied to the top surface. Vibration under pressure is particularly useful in masonry units and the consolidation of concrete production where the very stiff mixtures do not react favorably to vibration alone.

Centrifugation, vibration, and rolling may be combined in the production of concrete pipe and other hollow sections.

CHAPTER 4—CONSOLIDATION OF CONCRETE BY VIBRATION

Vibration consists of subjecting freshly placed concrete to rapid vibratory impulses, which liquefy the mortar (Fig. 4.1) and significantly reduce the internal friction between aggregate particles. While in this condition, concrete settles under the action of gravity (sometimes aided by other forces). When vibration is discontinued, friction is re-established.

4.1—Vibratory motion

A concrete vibrator has a rapid oscillatory motion that is transmitted to the freshly placed concrete. Oscillating motion is basically described in terms of frequency (number of oscillations or cycles per unit of time) and amplitude (deviation from point of rest).

Rotary vibrators follow an orbital path caused by rotation of an unbalanced eccentric mass inside a vibrator casing. The oscillation is essentially simple harmonic motion, as explained in the Appendix. Acceleration, a measure of intensity of vibration, can be computed from the frequency and amplitude when they are known. It is usually expressed as g, which is the ratio of the vibration acceleration to the acceleration of gravity. Acceleration is a useful parameter for external vibration, but not for internal vibration where the amplitude in concrete cannot be measured readily.

For vibrators other than the rotary type (for example, reciprocating vibrators), the principles of harmonic motion do not apply; however, the basic concepts described herein are still useful.

4.2—Process of consolidation

When low-slump concrete is deposited in the form, it is in a honeycombed condition, consisting of mortar-coated, coarse-aggregate particles and irregularly distributed pockets of entrapped air. Reading (1967) stated that the volume of entrapped air depends on the workability of the mixture, size and shape of the form, amount of reinforcing steel and other items of congestion, and method of depositing the concrete. The volume of entrapped air is in the range of 5 to 20%. Consolidation should remove practically all of the entrapped air, which is important because of its adverse effect on concrete properties.

Consolidation by vibration is best described as consisting of two stages—the first comprising subsidence or slumping of the concrete, and the second a de-aeration (removal of entrapped air bubbles). The two stages may occur simultaneously, with the second stage under way near the vibrator before the first stage has been completed at greater distances (Kolek 1963).

When vibration is started, impulses cause rapid disorganized movement of mixture particles within the vibrator's radius of influence. Radius of influence is the plan-view-area that a vibrator is able to produce sufficient impulses to consolidate concrete. The mortar is temporarily liquefied. Internal friction, which enabled the concrete to support itself in its original honeycombed condition, is reduced drastically. The mixture becomes unstable and seeks a lower level and denser condition.