

Guide for Consolidation of Concrete

Reported by ACI Committee 309

Richard E. Miller
Chair

Jerome H. Ford
Subcommittee Chair

Neil A. Cumming
Timothy P. Dolen
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.

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

CONTENTS

Chapter 1—General, p. 309R-2

Chapter 2—Effect of mixture proportions on consolidation, p. 309R-3

- 2.1—Mixture proportions
- 2.2—Workability and consistency
- 2.3—Workability requirements

Chapter 3—Methods of consolidation, p. 309R-4

- 3.1—Manual methods
- 3.2—Mechanical methods
- 3.3—Methods used in combination

Chapter 4—Consolidation of concrete by vibration, p. 309R-5

- 4.1—Vibratory motion
- 4.2—Process of consolidation

Chapter 5—Equipment for vibration, p. 309R-6

- 5.1—Internal vibrators
- 5.2—Form vibrators
- 5.3—Vibrating tables
- 5.4—Surface vibrators
- 5.5—Vibrator maintenance

ACI 309R-05 became effective August 5, 2005 and supersedes ACI 309R-96.
Copyright © 2005, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording, or by any information storage or retrieval system, or device, unless permission in writing is obtained from the copyright proprietor.

Chapter 6—Forms, p. 309R-13

- 6.1—General
- 6.2—Sloping surfaces
- 6.3—Surface blemishes
- 6.4—Form tightness
- 6.5—Forms for external vibration

Chapter 7—Recommended vibration practices for general construction, p. 309R-15

- 7.1—General
- 7.2—Procedure for internal vibration
- 7.3—Adequacy of internal vibration
- 7.4—Vibration of reinforcement
- 7.5—Revibration
- 7.6—Form vibration
- 7.7—Consequences of improper vibration

Chapter 8—Structural concrete, p. 309R-19

- 8.1—Design and detailing prerequisites
- 8.2—Mixture requirements
- 8.3—Internal vibration
- 8.4—Form vibration
- 8.5—Tunnel linings

Chapter 9—Mass concrete, p. 309R-20

- 9.1—Mixture requirements
- 9.2—Vibration equipment
- 9.3—Forms
- 9.4—Vibration practices
- 9.5—Roller-compacted concrete

Chapter 10—Normal-density concrete floor slabs, p. 309R-22

- 10.1—Mixture requirements
- 10.2—Equipment
- 10.3—Structural slabs
- 10.4—Slabs on ground
- 10.5—Heavy-duty industrial floors
- 10.6—Vacuum dewatering

Chapter 11—Pavements, p. 309R-24

- 11.1—General
- 11.2—Mixture requirements
- 11.3—Equipment
- 11.4—Vibration procedures
- 11.5—Special precautions

Chapter 12—Precast products, p. 309R-27

- 12.1—General
- 12.2—Mixture requirements
- 12.3—Forming material
- 12.4—Choice of consolidation method
- 12.5—Placing methods

Chapter 13—Structural low-density concrete, p. 309R-28

- 13.1—General
- 13.2—Mixture requirements
- 13.3—Behavior of structural low-density concrete during vibration

- 13.4—Consolidation equipment and procedures
- 13.5—Floors

Chapter 14—High-density concrete, p. 309R-29

- 14.1—General
- 14.2—Mixture requirements
- 14.3—Placing techniques

Chapter 15—Self-consolidating concrete, p. 309R-29

- 15.1—General

Chapter 16—Quality control and quality assurance, p. 309R-29

- 16.1—General
- 16.2—Adequacy equipment and procedures
- 16.3—Checking equipment performance

Chapter 17—Consolidation of test specimens, p. 309R-31

- 17.1—Strength
- 17.2—Density
- 17.3—Air content
- 17.4—Consolidating very stiff concrete in laboratory specimens

Chapter 18—Consolidation in congested areas, p. 309R-32

- 18.1—Common placing problems
- 18.2—Consolidation techniques

Chapter 19—References, p. 309R-33

- 19.1—Referenced standards and reports
- 19.2—Cited references

Appendix—Fundamentals of vibration, p. 309R-35

- A.1—Principles of simple harmonic motion
- A.2—Action of a rotary vibrator
- A.3—Vibratory motion in the concrete

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. **Documents** Alternatively, the concrete is properly consolidated. **Document Sharing Hub**



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 requires the ease and homogeneity with which concrete can be mixed, placed,

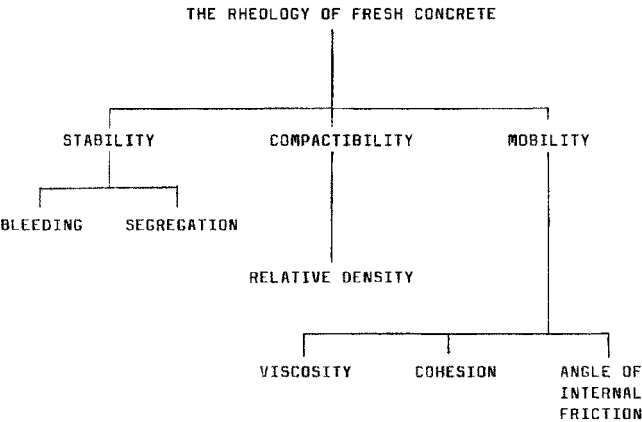


Fig. 2.1—Parameters of rheology of fresh concrete.

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 structure becomes unstable and seeks a lower level and denser condition.



Fig. 4.1—Internal vibratory “liquefying” low-slump concrete.

It flows laterally to the form and around the reinforcing steel and embedments.

At the completion of this first stage, honeycomb has been eliminated; the large voids between the coarse-aggregate particles are now filled with mortar. The concrete behaves somewhat like a liquid containing suspended coarse-aggregate particles. The mortar still contains many entrapped air bubbles, however, ranging up to perhaps 1 in. (25 mm) across and amounting to several percent of the concrete volume.

After consolidation has proceeded to a point where the coarse aggregate is suspended in the mortar, further agitation of the mixture by vibration causes entrapped air bubbles to rise to the surface. Large air bubbles are more easily removed than small ones because of their greater buoyancy. Also, those air bubbles near the vibrator are released before those near the outer fringes of the radius of influence.

The vibration process should continue until the entrapped air is reduced sufficiently to attain a concrete density consistent with the intended strength and other requirements of the mixture. To remove all of the entrapped air with standard vibrating equipment is usually not practical.

ACI 309.1R describes the mechanism and principles involved in vibration of fresh concrete.

CHAPTER 5—EQUIPMENT FOR VIBRATION

Concrete vibrators can be divided into two main classes—internal and external. External vibrators may be further divided into form vibrators, surface vibrators, and vibrating tables.

5.1—Internal vibrators

Internal vibrators, often called spud or poker vibrators, have a vibrating casing or head, and may have a flexible shaft. The head is immersed in and acts directly against the concrete. In most cases, internal vibrators depend on the cooling effect of the surrounding concrete to prevent overheating.

All internal vibrators presently in use are the rotary type (Section 4.1). The vibratory impulses emanate at right angles to the head.

5.1.1 Flexible-shaft type—This type of vibrator is probably the most widely used. The eccentric mass is usually driven by an electric or pneumatic motor, or by a portable internal combustion engine (Fig. 5.1(a)).

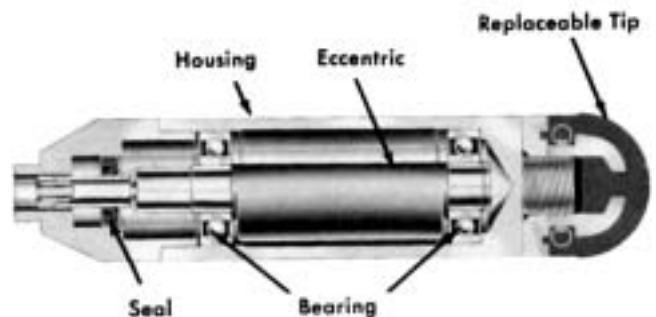


Fig. 5.1(a)—Flexible shaft vibrators; electric motor-driven type (top); gasoline engine-driven type (middle); and cross section through head (bottom).

For the electric motor-driven type, a flexible drive shaft leads from the electric motor into the vibrator head where it turns the eccentric mass. The motor generally has a nominal 120 V (occasionally 240), single phase, 60 Hz alternating current.

current characteristics. Fifty Hz AC current is used in some countries. The frequency of this type of vibrator is quite high when operating in air—generally in the range of 12,000 to 17,000 vibrations per min (200 to 283 Hz) (the higher values being for the smaller head sizes). When operating in concrete, however, the frequency is usually reduced by approximately 1/5. In this report, frequency is expressed in vibrations per min to conform to current industry practice in the United States; however, frequency is given in hertz in the Appendix to agree with textbook formulas.



Fig. 5.1(b)—Backpack two-cycle gasoline engine-driven vibrator.

For the engine-driven types, both gasoline and diesel, the engine speed is usually approximately 3600 rpm (60 Hz). A V-belt drive or gear transmission is used to step up this speed to an acceptable frequency level. Another type of unit uses a two-cycle gasoline engine operating at a no-load speed of 12,000 rpm (Fig. 5.1(b)), so the need for a step-up transmission is eliminated. This unit is portable and is usually carried on a backpack. Again, a flexible shaft leads into the vibrator head. While larger and more cumbersome than electric motor-driven vibrators, engine-driven vibrators are attractive where commercial power is not readily available.

For most flexible-shaft vibrators, the frequency is the same as the speed of the shaft. However, the roll-gear (conical-pendulum) type is able to achieve high vibrator frequency with a modest electric motor and flexible shaft speeds. The end of the pendulum strikes the inner housing in a star-shaped pattern, giving the vibrator head a frequency higher than the shaft driving it. Motor speeds are usually approximately 3600 rpm with a 60 Hz current (approximately 3000 rpm with a 50 Hz current). A single induction or three-phase squirrel cage motor is generally used. The low speed of the flexible shaft is favorable from the standpoint of maintenance.

5.1.2 Electric motor-in-head type—Electric motor-in-head vibrators have increased in popularity in recent years (Fig. 5.2). Because the motor is in the vibrator head, there is no separate motor and flexible drive to handle. A substantial electrical cable, which also acts as a handle, leads into the



Fig. 5.2—Electric motor-in-head vibrator; external appearance (top) and internal construction of head (bottom).



Fig. 5.3—Air vibrators for ordinary construction (top) and for mass concrete (bottom).

head. Electric motor-in-head vibrators are generally at least 2 in. (50 mm) in diameter.

This type of vibrator is available in two designs. One uses a universal motor and the other a 180 Hz (high cycle) three-phase motor. In the latter, the energy is usually supplied by a portable gasoline engine-driven generator; however, commercial power passed through a frequency converter may be used. The design uses an induction-type motor that has little drop-off in speed when immersed in concrete. It can rotate a heavier eccentric mass and develops a greater centrifugal force than current universal motor-in-head models of the same diameter. Vibrator motors operating on 150 or 200 Hz current are used in some countries.

5.1.3 Pneumatic vibrators—Pneumatic vibrators (Fig. 5.3) are operated by compressed air, with the pneumatic motor generally being inside the vibrator head. The vane type has been the most common, with both the motor and the eccentric elements supported on bearings. Bearingless models, which generally require less maintenance, are also available, as are a few flexible-shaft pneumatic models, with the air motor outside the head.

Pneumatic vibrators are useful where compressed air is the most readily available source of power. The frequency is highly dependent on the air pressure. Therefore, the air pressure should always be maintained at the proper level, usually that recommended by the manufacturer. In some cases, it is desirable to vary the air pressure to obtain a different frequency.

5.1.4 Hydraulic vibrators—Hydraulic vibrators, using a hydraulic gear motor, are popular on paving machines. The vibrator is connected to the paver's hydraulic system by means of high-pressure hoses. The frequency of vibration can be regulated by varying the rate of flow of hydraulic fluid through the vibrator. The efficiency of the vibrator is dependent on the pressure and flow rate of the hydraulic fluid. Therefore, it is important that the hydraulic system be checked frequently.

5.1.5 Selecting an internal vibrator for the job—Effectiveness in consolidating concrete is the principal requirement for an internal vibrator. It should have an adequate radius of influence, and it should be capable of flattening and de-airing the concrete quickly. The vibrator should be reliable in operation, easy to handle and manipulate, resistant to wear, and be such that it does not damage embedded items. Some of these requirements are mutually opposed, so compromises are necessary; however, some of the problems can be minimized or eliminated by careful vibrator design. For example, very high frequencies and high centrifugal force tend to increase maintenance requirements and reduce the life of vibrators.

ACI 309.1R indicates that the effectiveness of an internal vibrator depends mainly on the head diameter, frequency, and amplitude. The amplitude is largely a function of the eccentric moment and head mass, as explained in the [Appendix](#).

Frequency may be readily determined ([Section 16.3.1](#)), but no simple method exists for determining the amplitude of a vibrator operating in concrete. Therefore, it is necessary to use the amplitude as determined while the vibrator is operating in air, which is somewhat greater than the amplitude in concrete. This amplitude may be either measured or computed, as described in [Section 16.3.2](#). While not strictly correct for internal vibrators, the centrifugal force may be used as a rough overall measure of the output of a vibrator. [Figure A.2](#) in the Appendix explains how it is computed.

The radius of influence, and hence the insertion spacing, depends not only on the characteristics of the vibrator but also on the workability of the mixture and degree of congestion.

[Table 5.1](#) gives the ordinary range of characteristics, performance, and applications of internal vibrators. (Some special-purpose vibrators fall outside these ranges.) Recommended frequencies are given, along with suggested values of eccentric moment, average amplitude, and centrifugal force. Approximate ranges are also given for the radius of influence and rate of concrete placement. These are empirical values based mainly on previous experience.

Equally good results can usually be obtained by selecting a vibrator from the next larger group, provided in [Table 5.1](#). In selecting the vibrator and vibration procedures, consideration should be given to the vibrator size relative to the form size. Cracking of formed concrete surfaces is exacerbated by drying shrinkage that occurs in the high concentration of cement paste brought to the surface by a vibrator too large for the application.

The values in [Table 5.1](#) are not to be considered as a guarantee of performance under all conditions. The best measure of vibrator performance is its effectiveness in consolidating job concrete.

Table 5.1—Range of characteristics, performance, and applications of internal* vibrators, flexible shaft, and motor-in-head vibrators

Group	Diameter of head, in. (mm)	Recommended frequency, [†] vibrations per min (Hz)	Suggested values			Approximate values		Application
			Eccentric moment, [‡] in.-lb (mm-kg)	Average amplitude, [§] in. (mm)	Centrifugal force, lb (kN)	Radius of influence, ^{***} in. (mm)	Rate of concrete placement, ^{**††} yd ³ /h (m ³ /h)	
1	3/4 to 1-1/2 (20 to 40)	9000 to 15,000 (150 to 250)	0.03 to 0.10 (0.4 to 1.2)	0.015 to 0.03 (0.4 to 0.8)	100 to 400 (0.4 to 1.8)	3 to 6 (75 to 150)	1 to 5 (1 to 4)	Plastic and flowing concrete in very thin members and confined places. May be used to supplement larger vibrators, especially in prestressed work where cables and ducts cause congestion in forms. Also used for fabricating laboratory test specimens.
2	1-1/4 to 2-1/2 (30 to 65)	8500 to 12,500 (140 to 210)	0.08 to 0.25 (0.9 to 2.9)	0.02 to 0.04 (0.5 to 1.0)	300 to 900 (1.3 to 4.0)	5 to 10 (125 to 250)	3 to 10 (2 to 8)	Plastic concrete in thin walls, columns, beams, precast piles, thin slabs, and along construction joints. May be used to supplement larger vibrators in confined areas.
3	2 to 3-1/2 (50 to 90)	8000 to 12,000 (130 to 200)	0.20 to 0.70 (2.3 to 8.1)	0.025 to 0.05 (0.6 to 1.3)	700 to 2000 (3.1 to 8.9)	7 to 14 (175 to 350)	6 to 20 (5 to 15)	Stiff plastic concrete 3 in. (less than 75 mm) slump in general construction such as walls, columns, beams, prestressed piles, and heavy slabs. Auxiliary vibration adjacent to forms of mass concrete and pavements. May be gang-mounted to provide full-width internal vibration of pavement slabs.
4	3 to 6 (75 to 150)	7000 to 10,500 (120 to 180)	0.70 to 2.5 (8.1 to 29)	0.03 to 0.06 (0.8 to 1.5)	1500 to 4000 (6.7 to 18)	12 to 20 (300 to 500)	15 to 40 (11 to 31)	Mass and structural concrete of 2 in. (50 mm) slump deposited in quantities up to 4 yd ³ (3 m ³) in relatively open forms of heavy construction (powerhouses, heavy bridge piers, and foundations). Also, auxiliary vibration in dam construction near forms and around embedded items and reinforcing steel.
5	5 to 7 (125 to 175)	5500 to 8500 (90 to 140)	2.25 to 3.50 (26 to 40)	0.04 to 0.08 (1.0 to 2.0)	2500 to 6000 (11 to 27)	16 to 24 (400 to 600)	25 to 50 (19 to 38)	Mass concrete in gravity dams, large piers, and massive walls. Two or more vibrators will be required to operate simultaneously to mix and consolidate quantities of concrete of 4 yd ³ (3 m ³) or more deposited at one time in the form.

*Generally, extremely dry or very stiff concrete (Table 2.1) does not respond well to internal vibrators.

[†]While vibrator is operating in concrete.

[‡]Computed by formula in Fig. A.2 in Appendix.

[§]Computed or measured as described in Section 16.3.2. This is peak amplitude (half the peak-to-peak value), operating in air.

^{||}Computed by formula in Fig. A.2 in Appendix, using frequency of vibrator while operating in concrete.

^{***}Distance over which concrete is fully consolidated.

^{**}These ranges reflect not only the capability of the vibrator but also differences in workability of the mixture, degree of de-aeration desired, or other conditions experienced in construction.

^{††}Assumes the insertion spacing is 1-1/2 times the radius of influence, and that vibrator operates two-thirds of time concrete is being placed.

5.1.6 Special shapes of vibrator heads—The recommendations in Table 5.1 assume round vibrator heads. Other shapes of vibrator heads such as square or other polygonal shapes, fluted, and finned, have different surface areas and different distributions of force between the vibrator and the concrete (Fig. 5.4).

The effect of shape on vibrator performance has not been thoroughly evaluated. For the purpose of this guide, the equivalent diameter of a specially shaped vibrator should be considered as that of a round vibrator having the same perimeter.

5.1.7 Data to be supplied by manufacturer—The vibrator manufacturer's catalog should include the physical dimensions (length and diameter) and total mass of the vibrator head, eccentric moment, frequency in air and approximate frequency in concrete, and centrifugal force at these two frequencies. The catalog should also include certain other data needed for proper hookup and operation of the vibrators. Voltage and current requirements and wire sizes (depending on the length of run) for electric vibrators should be given. For pneumatic vibrators, compressed air pressure and flow capacity should be stated as well as the size of piping or hose



Fig. 5.4—Several of the different sizes and shapes of vibrator heads available. From left to right: short head, round head, square head, hexagonal head, and rubber-tipped head.

(also depending on the length of run). Speed should be given for gasoline-engine driven units.

Information for hydraulic vibrators should include recommended operating pressures and a chart showing frequency at various flow rates.



Fig. 5.5—Rotary form vibrators: pneumatically driven (top) and electrically driven (bottom).

5.2—Form vibrators

5.2.1 General description—Form vibrators are external vibrators attached to the outside of the form or mold. They vibrate the form, which in turn transmits the vibration to the concrete. Form vibrators are self-cooling and may be of either the rotary or reciprocating type.

Concrete sections as thick as 24 in. (600 mm) and up to 30 in. (750 mm) deep have been effectively vibrated by form vibrators in the precast concrete industry. For walls and deeper placements, it may be necessary to supplement a form vibrator with internal vibration for sections thicker than 12 in. (300 mm).

5.2.2 Types of form vibrators

5.2.2.1 Rotary—Rotary form vibrators produce essentially simple harmonic motion. The impulses have components both perpendicular to and in the plane of the form. This type may be pneumatically, hydraulically, or electrically driven (Fig. 5.5).

In the pneumatically and hydraulically driven models, centrifugal force is developed by a rotating cylinder or revolving eccentric mass (similar to internal vibrators). These vibrators generally work at frequencies of 6000 to 12,000 vibrations per min (100 to 200 Hz). The frequency may be varied by adjusting the air pressure on the pneumatic models or the fluid pressure on the hydraulic models.

The electrically driven models have an eccentric mass attached to each end of the motor shaft. Generally, these masses are adjustable. In most cases, induction motors are



Fig. 5.6—Reciprocating form vibrator.

used and the frequency is 3600 or 3000 vibrations per min (60 or 50 Hz AC). Higher frequency vibrators operating at 7200 or 10,800 vibrations per min (120 or 180 Hz) are also available (6000, 9000, or 12,000 vibrations per min [100, 150, or 200 Hz] in Europe). These higher frequency vibrators require a frequency converter. There are also electric form vibrators with frequencies of 6000 to 9000 vibrations per min (100 to 150 Hz) that are powered by single-phase universal motors.

The manufacturer's catalog should include physical dimensions, mass, and eccentric moment. For pneumatically driven models, frequency in air and approximate frequency under load should be given. For electric models, the frequency at the rated electric load should be stated. The centrifugal force at the given frequency values should be provided. In addition, the catalog should provide data needed for proper hookup of the vibrators (as in Section 5.1.7).

5.2.2.2 Reciprocating—In reciprocating vibrators, a piston is accelerated in one direction, stopped (by impacting against a steel plate), and then accelerated in the opposite direction (Fig. 5.6). This type is pneumatically driven, and frequencies are usually in the range of 1000 to 5000 vibrations per min (20 to 80 Hz). These vibrators produce impulses acting perpendicular to the form. The principles of simple harmonic motion do not apply.

5.2.2.3 Other types—Other types of form vibrators, less commonly used, include:

- Electromagnetic, which usually develops a combination sinusoidal-saw-tooth waveform; and
- Pneumatic or electric hand-held hammers, which are sometimes used to assist in consolidating small concrete units.

5.2.3 Selecting external vibrators for vertical forms—

Low-frequency, high-amplitude vibration is normally preferred for stiffer mixtures. High-frequency, low-amplitude vibration generally results in better consolidation and better surfaces

(fewer bugholes) for more plastic consistencies. In this guide, the dividing line between high and low frequency for external vibration is arbitrarily taken as 6000 vibrations per min (100 Hz), and between high and low amplitude 0.005 in. (0.13 mm), respectively.

The effectiveness of form vibrators is largely a function of the acceleration imparted to the concrete by the form. Accelerations in the range of 1 to 2g ($1g = 9.81 \text{ m/s}^2 = 386 \text{ in./s}^2$), standard acceleration of gravity are generally recommended for plastic mixtures and 3 to 5g for stiff mixtures. In addition, the amplitude should not be less than 0.001 in. (0.025 mm) for plastic mixtures or 0.002 in. (0.050 mm) for stiff mixtures.

The acceleration of a form is a function of the centrifugal force of the vibrators as related to the mass of the form and activated concrete. The following empirical formulas recommended by Forssblad (1971) have been found useful in estimating the centrifugal force of form vibrators needed to provide adequate consolidation.

1. For plastic mixtures in beam and wall forms

$$CF = 0.5(MF + 0.2MC)$$

where CF = centrifugal force; MF = mass of form; and MC = mass of concrete.

2. For stiff mixtures in pipe and other rigid forms

$$CF = 1.5(MF + 0.2MC)$$

Formulas should be checked against field experience. The prospective user submits drawings of the structure to be vibrated to the vibrator manufacturer and solicits recommendation as to size, quantity, and location of vibrator units. The proper distance between form vibrators is normally within the range of 5 to 8 ft (1.5 to 2.5 m), and supplemental internal vibration may be required for sections thicker than 12 in. (300 mm).

Frequency and amplitude should be checked at several points on the form with a vibrograph or other suitable device (Sections 16.3.1 and 16.3.2). The actual acceleration can be computed from these values using the formula in Fig. A.2. Frequency and amplitude measurements can also be very useful in establishing optimum spacing and orientation of form vibrators. One should recognize that there is always the likelihood that dead spots on forms will occur. Thus, it is important to locate external vibrators to reduce the increments of dead spots, or supplement with internal vibrators.

When external vibration employs electrically operated vibrators on thin form members, caution should be used to prevent burning out these vibrators.

5.3—Vibrating tables

A vibrating table normally consists of a steel or reinforced concrete table with external vibrators rigidly mounted to the supporting frame (Fig. 5.7). The table and frame are isolated from the base by steel springs, neoprene isolation pads, or other means.

The table itself can be part of the mold, although a separate mold usually rests on top of the table. Vibration is transmitted



Fig. 5.7—Vibrating table.

from the table to the mold and to the concrete. The advisability of fastening the mold to the table is open to debate.

Low frequency (6000 vibrations per min [below 100 Hz]), high amplitude (0.005 in. [over 0.13 mm]) vibration is normally preferred, at least for stiffer mixtures.

The effectiveness of table vibration is largely a function of the acceleration imparted to the concrete by the table. Accelerations in the range of 3 to 10g (30 to 100 m/s^2) are generally recommended, the higher values being needed for the stiffer mixtures. In addition, the amplitude should not be less than 0.001 in. (0.025 mm) for plastic mixtures or 0.002 in. (0.050 mm) for stiff mixtures.

Acceleration of the table is a function of the vibrational force as related to the mass of form and activated concrete. Three empirical formulas have been useful in estimating the required centrifugal force of the vibrators (Forssblad 1971):

1. Rigid vibrating table or vibrating beams, with the form placed loosely on the table

$$CF = (2 \text{ to } 4)(MT + 0.2MF + 0.2MC)$$

where CF = centrifugal force; MT = mass of table; MF = mass of form; and MC = mass of concrete.

2. Rigid vibrating table, with form attached to the table

$$CF = (2 \text{ to } 4)(MT + MF + 0.2MC)$$

3. Flexible vibrating table, continuous over several supports

$$CF = (0.5 \text{ to } 1)(MT + 0.2MC)$$