

Guide for Consolidation of Concrete

Reported by ACI Committee 309

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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.

Keywords: admixtures; air; air entrainment; amplitude; centrifugal force; concrete blocks; concrete construction; concrete pavements; concrete pipes; concrete products; concrete slabs; concretes; consistency; consolidation; floors; formwork (construction); heavyweight concretes; inspection; lightweight aggregate concretes; maintenance; mass concrete; mixture proportioning; placing; plasticizers; precast concrete; quality control; reinforced concrete; reinforcing steels; segregation; surface defects; tamping; vacuum-dewatered concrete; vibration; vibrators (machinery); water-reducing admixtures; workability.

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CHAPTER 1—GENERAL

A mass of freshly placed concrete is usually honey-combed with entrapped air. If allowed to harden in this condition, the concrete will be nonuniform, weak, porous, and poorly bonded to the reinforcement. It will also have a poor appearance. The mixture must be consolidated if it is to have the properties normally 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, rodding, tamping, or some combination of these actions; it is also applicable to similar manipulation of other cementitious mixtures, soils, aggregates, or the like.

Drier and stiffer mixtures require greater effort to achieve proper consolidation. By using certain chemical admixtures, consistencies requiring reduced consolidation effort can be achieved at a lower water content. As the water content of the concrete is reduced, concrete quality (strength, durability, and other properties) improves, provided it is properly consolidated. Alternatively, the cement content can be lowered, reducing the cost while maintaining the same quality. If adequate consolidation is not provided for these drier or stiffer mixtures, the quality of the in-place concrete drops off 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, concrete surfaces have a highly pleasing appearance [see Fig. 1(a) through 1(c)].



Fig. 1(a)—Pleasing appearance of concrete in church construction



Fig. 1(b)—Pleasing appearance of concrete in utility building construction



Fig. 1(c)—Close-ups of surfaces resulting from good consolidation

CHAPTER 2—EFFECT OF MIXTURE PROPERTIES 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 detail in documents prepared by ACI Committee 211, as listed in [Chapter 18.1](#).

2.2—Workability and consistency

Workability of freshly mixed concrete is that property that determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished. Workability is a function of the rheological properties of the concrete.

As shown in [Fig. 2.2](#), workability may be divided into three main aspects:

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

Workability is affected by grading, particle shape, proportions of aggregate and cement, use of chemical and mineral 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 work-

Table 2.1—Consistencies used in construction**

Consistency description	Slump, in. (mm)	Vebe time, sec	Compacting factor average	Thaulow drop table revolutions
Extremely dry	—	32 to 18	—	112-56
Very stiff	—	18 to 10	0.70	56-28
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	14-7
Plastic	3 to 5 (75 to 125)	3 to 0*	0.90	<7
Highly plastic	5 to 7½ (125 to 190)	—	—	—
Flowing	7½ plus (190 plus)	—	0.95	—

*Test method is of limited value in this range.

**ACI 211.3 Table 2.3.1 (a)

ability is through changes in the consistency brought about by minor variations in the water content.

The slump test (ASTM C 143) is widely used to indicate consistency of mixtures used in normal construction. The Vebe test is generally recommended for stiffer mixtures.

Values of slump, compacting factor, drop table, 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 Kelly ball are available. These are not used as frequently as slump. Information on various consistency tests has been discussed by Neville (1981), Vollick (1966), and Popovics (1982).

2.3—Workability requirements

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

Mixtures having moderately high slump, small maximum-size aggregate, and excessive fine aggregate are frequently used because the high degree of flowability means less work in placing.

At the other extreme, it is inadvisable to use mixtures that are too stiff for conditions of consolidation. They will require

great consolidation effort and even then may not be adequately consolidated. Direction and guidance are often required to achieve the use of mixtures of lower slump or fine aggregate content, or a larger 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 for additional information on chemical admixtures. The use of fly ash, slag, or silica fume may also affect the consolidation of concrete by permitting placement with less consolidation effort. Refer to reports of ACI Committee 226 for more information regarding these materials. The amount of consolidation effort required with or without the use of admixtures can best be determined by trial mixtures under field conditions.

It is the workability of the mixture in the form that determines the consolidation requirements. Workability may be considerably less than at the mixer because of slump loss due to high temperature, false set, delays, or other cause.

CHAPTER 3—METHODS OF CONSOLIDATION

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

3.1—Manual methods

Some consolidation is caused by gravity as the concrete is deposited in the form. This is particularly true for well proportioned flowing mixtures where less additional consolidation effort is required.

Plastic or more flowable 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 and water pockets 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 laborious and costly.

The manual consolidation methods are generally only used on smaller nonstructural concrete placement.

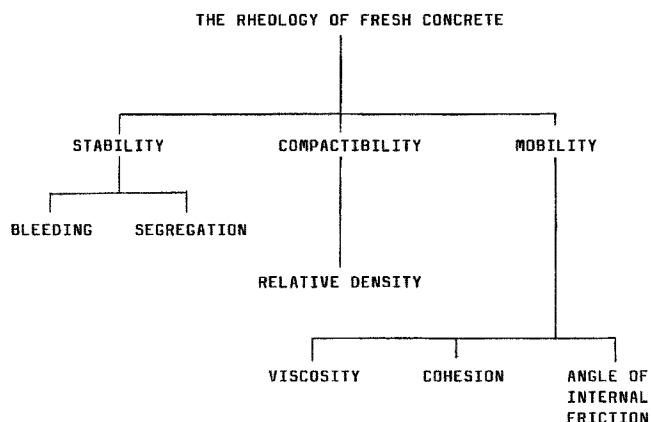


Fig. 2.2—Parameters of the rheology of fresh concrete



Fig. 4—Internal vibrator “liquifying” low-slump concrete

3.2—Mechanical methods

The most widely used consolidation method is vibration. It will receive the most attention in this guide. 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 blocks.

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, piles, poles, and other hollow sections.

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 $\frac{1}{8}$ to $\frac{1}{2}$ in. (3 to 13 mm).

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 re-

inforcement. 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 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 concrete block 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 (see Fig. 4) and drastically 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 reestablished.

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 weight or eccentric 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 by g ,

Table 5.1.5—Range of characteristics, performance, and applications of internal* vibrators

Column 1	2	3	4	5	6	7	8	9
Group	Diameter of head, in. (mm)	Recommended frequency, vibrations per min (Hz)	Suggested values of			Approximate values of		Application
			Eccentric moment, in. lb mm-k _g (10 ⁻³)	Average amplitude, in. (mm)	Centrifugal force, lb (kg)	Radius of action, in. (mm)	Rate of concrete placement, yd	
1	$\frac{3}{4}$ -1 $\frac{1}{2}$ (2-4) (20-40)	9000-15,000 (150-200)	0.03-0.10 (0.035-0.12) (3.5-12)	0.015-0.03 (0.04-0.08) (0.4-0.8)	100-400 (45-180)	3-6 (8-15) (80-150)	1-5 (0.8-4)	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 $\frac{1}{4}$ -2 $\frac{1}{2}$ (3-6) (30-60)	8500-12,500 (140-210)	0.08-0.25 (0.09-0.29) (9-29)	0.02-0.04 (0.05-0.10) (0.5-1.0)	300-900 (140-400)	5-10 (13-25) (130-250)	3-10 (2.3-8)	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	2-3 $\frac{1}{2}$ (5-9) (50-90)	8000-12,000 (130-200)	0.20-0.70 (0.23-0.81) (23-81)	0.025-0.05 (0.06-0.13) (0.6-1.3)	700-2000 (320-900)	7-14 (18-36) (180-360)	6-20 (4.6-15)	Stiff plastic concrete (less than 3-in. [80-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	3-6 (8-15) (80-150)	7000-10,500 (120-180)	0.70-2.5 (0.81-2.9) (81-290)	0.03-0.06 (0.08-0.15) (0.8-1.5)	1500-4000 (680-1800)	12-20 (30-51) (300-510)	(15-40) (11-31)	Mass and structural concrete of 0 to 2-in. (50 mm) slump deposited in quantities up to 4 yd ³ (3m 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	5-7 (13-18) (130-150)	5500-8500 (90-140)	2.25-3.50 (2.6-4.0) (260-400)	0.04-0.08 (0.10-0.20) (1.0-2.0)	2500-6000 (1100-2700)	16-24 (40-61) (400-610)	25-50 (19-38)	Mass concrete in gravity dams, large piers, massive walls, etc. 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.

Column 3—While vibrator is operating in concrete.

Column 4—Computed by formula in Fig. A.2 in Appendix A.

Column 5—Computed or measured as described in Section 15.3.2. This is peak amplitude (half the peak-to-peak value), operating in air.

Column 6—Computed by formula in Fig. A.2 in Appendix, using frequency of vibrator while operating in concrete.

Column 7—Distance over which concrete is fully consolidated.

Column 8—Assumes the insertion spacing is 1 $\frac{1}{2}$ times the radius of action, and that vibrator operates two-thirds of time concrete is being placed.

Columns 7 and 8—These ranges reflect not only the capability of the vibrator but also differences in workability of the mix, degree of deaeration desired, and other conditions experienced in construction.

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

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, reciprocating vibrators for example, the principles of harmonic motion do not apply. However, the basic concepts described here 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. It is generally in the range of 5 to 20 percent. The purpose of consolidation is to remove practically all of the entrapped air because of its adverse effect on concrete properties and surface appearance.

Consolidation by vibration is best described as consisting of two stages—the first comprising subsidence or slumping of the concrete, and the second a deaeration (removal of en-

trapped 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. 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. It flows laterally to the form and around the reinforcing steel and embeddings.

At the completion of this first stage, honeycomb has been eliminated; the large voids between the coarse aggregate are now filled with mortar. The concrete behaves somewhat like a liquid containing suspended coarse-aggregate particles. However, the mortar still contains many entrapped air bubbles, 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 near the vibrator are released before those near the outer fringes of the radius of action.

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.

The mechanism and principles involved in vibration of fresh concrete are described in detail in ACI 309.1R.

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. 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 (see 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 is usually driven by an electric or pneumatic motor, or by a portable internal combustion engine [see Fig. 5.1.1(a)].

For the electric motor-driven type, a flexible drive shaft leads from the electric motor into the vibrator head where it turns the eccentric weight. The motor generally has universal, 120 (occasionally 240) volt, single-phase, 60 Hz alternating-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). However, when operating in concrete, the frequency is usually reduced by about one-fifth. 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.

For the engine-driven types, both gasoline and diesel, the engine speed is usually about 3600 revolutions per min (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 2-cycle gasoline engine operating at a no-load speed of 12,000 RPM [Fig. 5.1.1.(b)], so the need for a step-up transmission is eliminated. This unit is portable and is usually carried on a back pack. 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 modest electric motor and flexible shaft speeds. The end of the

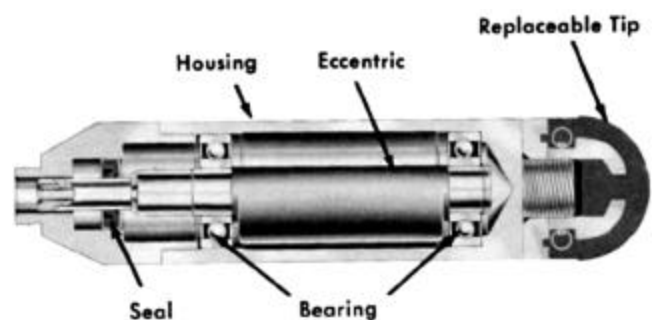


Fig. 5.1.1(a)—Flexible shaft vibrators; electric motor-driven type (top); gasoline engine-driven type (middle); and cross section through head (bottom)

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 about 3600 revolutions per min with 60 Hz current (about 3000 revolutions per min with 50 Hz current). A single induction or three-phase squirrel-cage motor

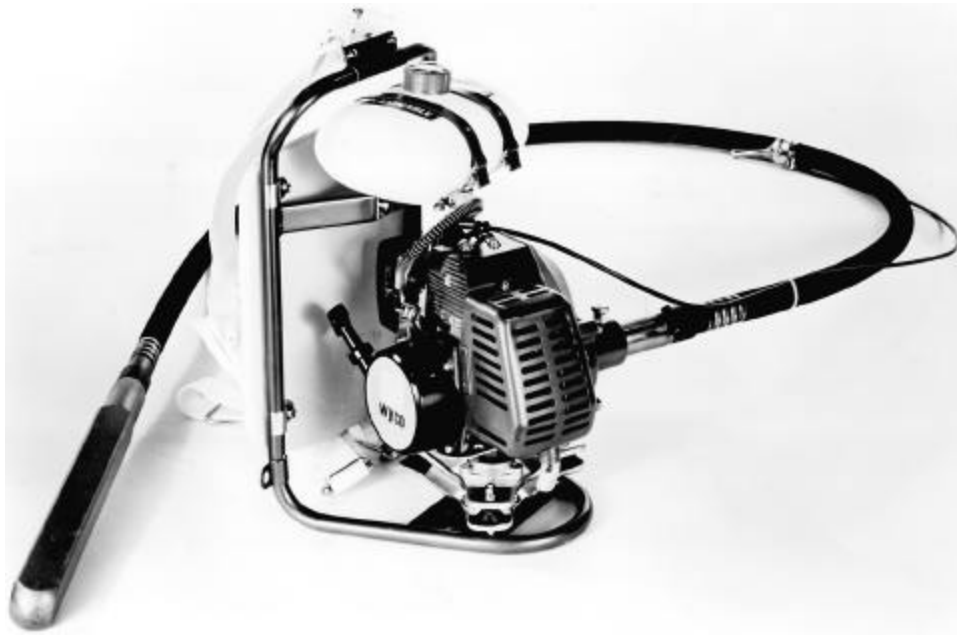


Fig. 5.1.1(b)—Back pack two-cycle gasoline engine-driven vibrator

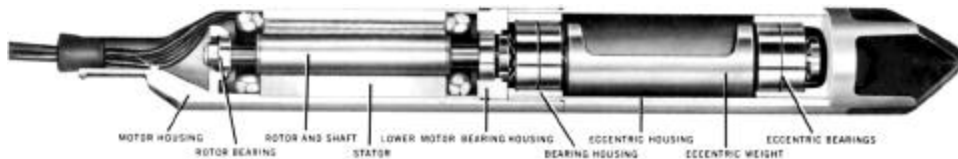


Fig. 5.1.2—Electric motor-in-head vibrator; external appearance (top) and internal construction of head (bottom)

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 (see Fig. 5.1.2). Since 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 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 dropoff in speed when immersed in concrete. It can rotate a heavier eccentric weight and develops a greater centrifugal force than current universal motor-in-head models of the

Table 5.5.1—Sample service log for flexible shaft vibrator

Model _____ Serial No. _____ Date purchased _____ Date checked out from equipment pool _____ Estimated use, hr per day _____			
Item	Frequency of preventive maintenance		
	Clean and inspect	Lubricate	Replace
	Electric motor		
Filter	---	---	---
Brushes	---	---	---
Switch	---	---	---
Armature and field	---	---	---
Bearings	---	---	---
	Flexible shaft		
Shaft	---	---	---
	Vibrator head		
Seals	---	---	---
Bearings	---	---	---
Oil change	---	---	---

same diameter. Vibrator motors operating on 150 or 200 Hz current are used in some countries.

5.1.3 Pneumatic vibrators—Pneumatic vibrators (see Fig. 5.1.3) are operated by compressed air, 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. A few flexible-shaft pneumatic models, with the air motor outside the head, are also available.

Pneumatic vibrators are attractive where compressed air is the most readily available source of power. The frequency is highly dependent on the air pressure, so 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. Here 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. It is, therefore, important that the hydraulic system be checked frequently.

5.1.5 Selecting an internal vibrator for the job—The principal requirement for an internal vibrator is effectiveness in consolidating concrete. It should have an adequate radius of action, and it should be capable of flattening and de-aerating the concrete quickly. Insofar as possible, the vibrator should also 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, it is known that very high frequencies and high centrifugal force tend to increase maintenance requirements and reduce the life of vibrators.

Evidence strongly 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.

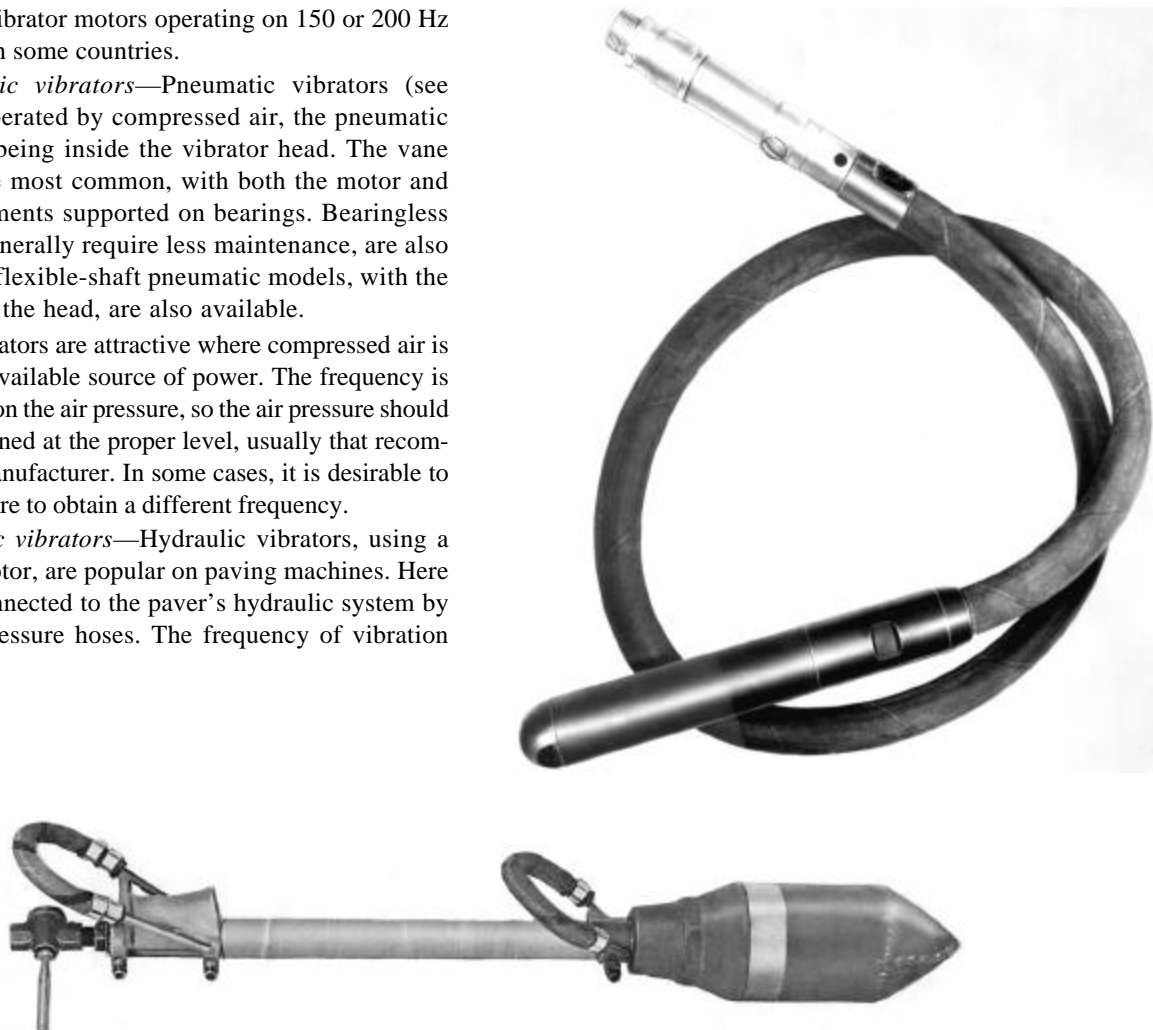


Fig. 5.1.3—Air vibrators for ordinary construction (top) and for mass concrete (bottom)

Frequency may be readily determined (see [Section 15.3.1](#)), but there is no simple method for determining amplitude of a vibrator operating in concrete. It is therefore 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 15.3.2](#).

While not strictly correct for internal vibrators, the centrifugal force may be used as a rough overall measure of the output of a vibrator. [Fig. A.2](#) in the Appendix explains how it is computed.

The radius of action, 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 5.1.5](#) 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 action 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 suitable adjustments are made in the spacing and time of the insertions. 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 due to 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 5.1.5](#) 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.

5.1.6 Special shapes of vibrator heads—The recommendations in [Table 5.1.5](#) assume round vibrators. Other shapes of vibrator head (square or other polygonal shapes, fluted,

finned, etc.), have a different surface area and have a different distribution of force between the vibrator and the concrete (see [Fig. 5.1.6](#)).

The effect of shape on vibrator performance has not been thoroughly evaluated. For the purpose of this guide, it is recommended that the equivalent diameter of a specially shaped vibrator 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 size of piping or hose (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.

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 (see [Fig. 5.2.2.1](#)).

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 used and the frequency is 3600 vibrations per min (60 Hz AC, or 3000 vibrations per min for 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 vibra-



Fig. 5.1.6—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

tions 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 di-

rection (see Fig. 5.2.2.2). 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:

a. Electromagnetic, which usually develops a combination sinusoidal-saw-tooth wave form.

b. 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).

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 2 g are generally recommended for plastic mixtures and 3 to 5 g 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.



Fig. 5.2.2.1—Rotary form vibrators; pneumatically driven (top) and electrically driven (bottom)

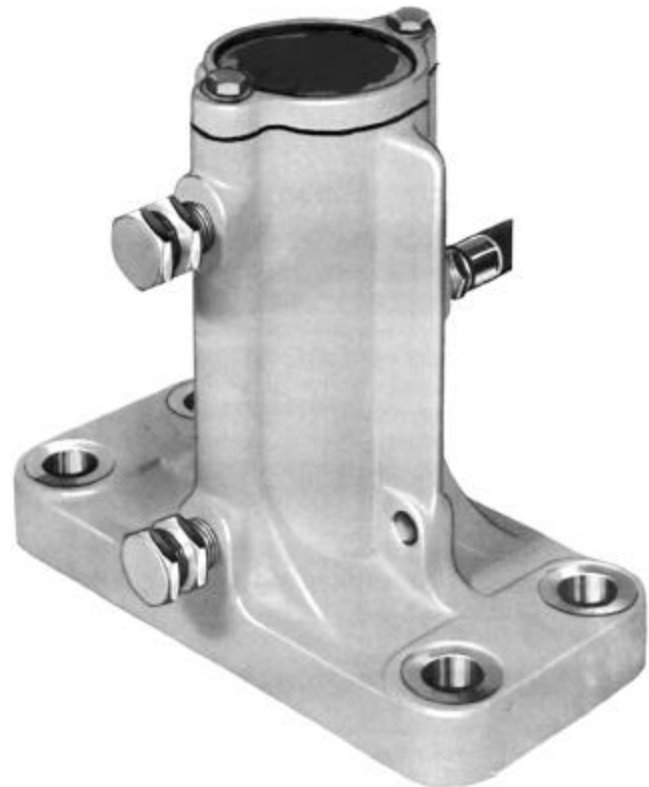


Fig. 5.2.2.2—Reciprocating form vibrator

The acceleration of a form is a function of the centrifugal force of the vibrators as related to the mass of form and concrete activated. 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: Centrifugal force = $0.5 [(mass\ of\ form) + 0.2 (concrete\ mass)]$.
2. For stiff mixtures in pipe and other rigid forms: Centrifugal force = $1.5 [(weight\ of\ form) + 0.2 (concrete\ weight)]$.

Formulas should be checked against field experience. The prospective user should submit drawings of the structure to be vibrated to the vibrator manufacturer and should solicit 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 (see Sections 7.5 and 15.3.3). From these values, the actual acceleration may be computed using the formula in Fig. A.1 in Appendix A.

When external vibration employs electrically operated vibrators on thin form membranes, 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 (see Fig. 5.3). The table and frame are isolated from the base by steel springs, neoprene isolation pads, or other means.



Fig. 5.3—Vibrating table

The table itself can be part of the mold. However, a separate mold usually rests on top of the table. Vibration is transmitted from the table to the mold and thence to the concrete. There is a difference of opinion as to the advisability of fastening the mold to the table.

Low frequency (below 6000 vibrations per min [100 Hz]), high amplitude (over 0.005 in. [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 10 g (30 to 100 m/sec²) 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 concrete activated. The following empirical formulas have been useful in estimating the required centrifugal force of the vibrators (Forssblad 1971):

1. Rigid vibrating table or vibrating beams, with form placed loosely on the table: Centrifugal force = $(2\ to\ 4) [(mass\ of\ table) + 0.2 (mass\ of\ form) + 0.2 (mass\ of\ concrete)]$.
2. Rigid vibrating table, with form attached to the table: Centrifugal force = $(2\ to\ 4) [(mass\ of\ table) + (mass\ of\ form) + 0.2 (mass\ of\ concrete)]$.
3. Flexible vibrating table, continuous over several supports: Centrifugal force = $(0.5\ to\ 1) [(mass\ of\ table) + 0.2 (mass\ of\ concrete)]$.

The choice of vibrators and spacing should be based on the preceding formulas and previous experience. Frequency and amplitude should be checked at several points on the table, with a vibrograph or other suitable device. The actual acceleration may then be computed. The vibrators should be moved around until dead spots are eliminated and the most uniform vibration is attained.

When concrete sections of different sizes are to be vibrated, the table should have a variable amplitude. Variable frequency is an added advantage.

If the vibrating table has a vibrating element containing only one eccentric, a circular vibrational motion may be obtained which imparts an undesirable rotational movement to the concrete. This may be prevented by mounting two vibrators side by side in such a manner that their shafts rotate in opposite directions. This neutralizes the horizontal component of vibration, so the table is subjected to a simple harmonic motion in the vertical direction only. Very high amplitudes may be obtained in this manner.

To achieve good consolidation of very stiff mixtures, it is frequently necessary to apply pressure to the top surface during vibration.

5.4—Surface vibrators

Surface vibrators are applied to the top surface and consolidate the concrete from the top down by maintaining a head of concrete in front of them. Their leveling effect assists the finishing operation. They are used mainly in slab construction.

There are three principal types of surface vibrators:



Fig. 5.4(a)—Vibrating screed for small jobs. Single beam type

a. *Vibrating screed*—This consists of a single or double beam spanning the slab width [see Fig. 5.4(a) and (b)]. Vibrating screeds are most suited for horizontal or nearly horizontal surfaces. Caution should be exercised in using vibrating screeds on sloping surfaces. One or more eccentrics, depending on the screed length, are attached to the top. The eccentrics are driven by an internal combustion engine, or by electric or pneumatic power. The beam is supported on the forms or suitable rails; this controls the screed elevation so that it acts not only as a compactor but also provides the final finish. Vibratory screeds are usually hand drawn on small jobs and power towed on larger ones.

Vibration produced by oscillation of the beam is transmitted to the concrete near the vibrating member. A large amplitude is needed, especially for stiffer consistencies, to attain a considerable depth of consolidation. Frequencies of 3000 to 6000 vibrations per min (50 to 100 Hz) have been found to be satisfactory. Vibrating screeds usually work best with accelerations of about 5 g. Research by Kirkham (1963) has shown that consolidation is proportional to the mass times the amplitude times the frequency divided by the machine's forward speed.

$$\text{Consolidation} \propto \frac{\text{Mass} \cdot \text{Amplitude} \cdot \text{Frequency}}{\text{Speed}}$$

b. *Plate or grid vibratory tampers*—This consists of a small vibrating plate or grid, usually a few square feet (about 0.2 m²) in area, that is moved over the slab surface. These vibrators work best on relatively stiff concrete.

c. *Vibratory roller screed*—This unit strikes off as well as consolidates. One model consists of three rollers in which the front acts as an eccentric and is the vibrating roller, rotating at 100 to 400 revolutions per min (1.7 to 6.7 Hz) (regulated according to the consistency of the mixture) in a direction opposite to the direction of movement. It knocks down, screeds, and provides mild vibration. This equipment is suitable for plastic mixtures.

Vibratory hand floats or trowels are also available. Small vibratory devices, electrically or pneumatically powered, attached to standard finishing tools provide for easier finishing.



Fig. 5.4(b)—Vibrating screed for small jobs. Double beam type

5.5—Vibrator maintenance

Vibration equipment uses an eccentric or out-of-balance mass; therefore, higher-than-normal loads are imposed on parts such as bearings.

Regardless of vibrator type, care should be given to its maintenance. The manufacturers usually issue manuals giving instructions for servicing their machines. Nevertheless, stand-by vibrators should always be on hand.

For electrical vibrators, precautions should be taken to prevent accidental electrical shock.

Periodic measurements of energy input to the vibrator system (motor, flex shaft [if used], and vibrator head) should be taken under no load to determine free-load losses. This can be useful to indicate pending failure.

Preventive maintenance is a system of planned inspections, adjustments, repairs, and overhauls. Preventive maintenance of vibratory equipment is necessary for it to operate at full effectiveness and to avoid production shutdowns. Certain items need daily attention, while others require less frequent care, as recommended by the vibrator manufacturer.

Usually, the contractor is responsible for vibrator maintenance. Sometimes, however (especially in the case of certain

mass-concrete vibrators), the contractor performs only the daily maintenance, with other servicing left to the manufacturer.

5.5.1 Preventive maintenance program—A file should be established with data on use and servicing requirements for each vibrator. Servicing requirements are obtained mainly from the manufacturer's service manual and spare parts list. The file might contain some or all of the following:

- a. Make, serial number, and date of purchase.
- b. Line voltage and amperage requirements for electrical vibrators, air volume consumed by air units, minimum cable or pipe sizes, and other pertinent information.
- c. Spare parts that are apt to wear out quickly. If these are difficult to procure, they should be carried in stock.
- d. Log giving a breakdown of service requirements, from the power source to the vibrator tip. Items of wear, items to lubricate and inspect in each stage, and the recommended lubricants and frequency of lubrication are listed.

Table 5.5.1 is a service log that might be used for a flexible-shaft vibrator. Starting with the date that the vibrator is checked out from the equipment pool, an actual calendar schedule can be set up for the items listed. For best results this program should be handled by a separate maintenance division rather than the operating line.

CHAPTER 6—FORMS

Formwork, form release agents, mixture design, and consolidation are some key factors in establishing the appearance of concrete work. The concrete surface appearance is a reflection of the form surface, provided that consolidation is properly accomplished. Since repairs to a defective surface are costly and seldom fully satisfactory, they should be avoided by establishing and maintaining quality forming and consolidation procedures.

6.1—General

Form strength, design, and other requirements are covered in ACI 347R and ACI SP-4, *Formwork for Concrete* (Hurd 1989). These publications deal mainly with forms for concrete that is internally vibrated. Very little guidance is given on the design of forms for external vibration.

6.2—Sloping surfaces

It is difficult to consolidate concrete that has a sloping top surface. When the slope is approximately 1:4 (vertical to horizontal) or steeper, consolidation is best assured by providing a temporary holding form or slipform screed to prevent sag or flow of concrete during vibration. An advantage of the temporary holding form or slipform screed is elimination of the need to strike off the top surface (Tuthill 1967). The holding form can be removed before the concrete has reached its final set so that surface blemishes can be removed by hand. When the sloping form cannot be removed before the concrete has set, the form should be removed as soon as possible to permit filling of the blemishes.

6.3—Surface defects

Some surface defects are related to a combination of the consolidation process and formwork details. Formwork con-

siderations are addressed by ACI 347R, while ACI 303R provides information on the use of form release agents.

The formed concrete finish should be observed when the form is stripped so that appropriate corrective measures can be expeditiously implemented. Additional information concerning surface defects may be found in ACI 309.2R.

6.4—Form tightness

Form joints should be mortar-tight for all concrete construction and should be taped to prevent leakage where appearance is important. If holes, open joints, or cracks occur in the form sheathing, hydrostatic pressure will cause mortar to flow out when vibration momentarily converts it to a fluid consistency. Such loss of mortar will cause rock pockets or sand streaks at these locations (see Fig. 6.4). Also, air may sometimes be sucked into the form at points of leakage, causing additional voids in the concrete surface. These imperfections seriously impair surface appearance and in some cases may weaken the structure. Moreover, it is practically impossible to make repairs that are inconspicuous.

Forms may also lose mortar at the bottom during vibration if the bottom plate does not fit the base tightly. The forms may cause this leakage by floating upward during vibration, especially if one or both sides are battered. Forms must be securely tied down and tightly caulked if this leakage is to be prevented.



Fig. 6.4—Sand streaks caused by mortar leak



Fig. 6.5.3—Mounting of vibrators; wood wall form and pipe form (inset)

A 1 by 4 in. (25 by 100 mm) closed-cell rubber or polyvinylchloride foam strip tacked to the underside of the plate is quite effective in stopping this leakage. It is very helpful to secure flat, straight surfaces on which to set the plate.

Mortar leakage at form joints between form panels and at the bottom of wall forms can be minimized by extending the form sheathing about $\frac{1}{8}$ in. (3 mm), or more in some cases, beyond the form-framing members. This arrangement allows the relatively thin edges of the sheathing to conform more easily and tightly to adjacent surfaces than wide and unyielding faces of form-framing members. When it is desired to disguise the joints, rustication strips should be used.

ACI 347R and SP-4 (Hurd 1989) suggest a 1 in. (25 mm) or less overlap for form sheathing. Otherwise forms spread and promote loss of mortar. The wales should overlap the casting below and should be held tightly to the previous casting by form ties. Anchors or bolts in the previous placement are recommended.

6.5—Forms for external vibration

6.5.1 General—Forms must withstand the lateral pressure of the vibrating liquefied concrete. Forms for external vibration must also be able to stand up under the repeated, reversing stresses induced by vibrators attached to the forms. Furthermore, they must be capable of transmitting the vibration over a considerable area in a uniform manner. Form de-

sign and vibration requirements should be coordinated before purchasing the forms.

The low-frequency, high-amplitude type of vibration has a greater impact and is harder on forms than the high-frequency, low-amplitude type. Extremely rugged forms are required where high-frequency, high-amplitude vibration is used.

6.5.2 Forming material—Steel is the preferred forming material because it has good structural strength and fatigue properties, is well suited for attachment of vibrators, and when properly reinforced provides good, uniform transmission of vibration. Wood, plastic, or reinforced concrete forms are generally less suitable, but will give satisfactory results if their limitations are understood and proper allowances are made.

6.5.3 Design and construction—Forms should be designed to resist the pressure of concrete without excessive deflection and to transmit the vibratory impulses to the concrete. A steel plate, $\frac{3}{16}$ to $\frac{3}{8}$ in. (5 to 10 mm) or thicker, stiffened with vertical and/or horizontal ribs, will perform these functions. Oscillation (flexing) of the steel plate between the stiffeners is normally somewhat greater than for the stiffeners themselves, but it should not be excessive if the stiffeners are closely spaced. Special attention should be directed to attachments when external vibration is anticipated to insure that excessive form deflections do not occur.

Special members, such as steel I-beams or channels, should be placed next to the plate, passing through the stiffeners in a continuous run. It is generally desirable to weld the stiffeners to these members.

The vibrators should be rigidly attached to the special members (see Fig. 6.5.3). Damage to the form and vibrator will occur if the vibrator shakes loose.

When rotary electric units are used, the rigidity of mounting required can readily be determined by measuring the amperage draw. If it exceeds the nameplate rating, the support is not strong enough. Air units cannot be evaluated as easily, but observing the movement of the form gives an indication of the rigidity. It is essential that the form hardware be securely fastened. Since wedges have a tendency to work loose under vibration, bolting is more dependable. Special attention should be paid to the strength of welds.

Vertical forms should be placed on rubber pads or other resilient base material to prevent transmission and loss of vibration to the supporting foundation as well as leakage of mortar.

It is difficult to attain and maintain form tightness when vibration is of the external type; even minute openings in the form will permit loss of mortar. Rubber or other suitable seals may be used to prevent grout loss through steel forms.

Attaching external vibrators directly to the form is generally unsatisfactory because the skin may flutter or develop a diaphragm action. This movement causes the vibrational force to be highly localized, and sometimes results in early form failure. However, portable vibrators mounted to brackets on metal forms have been successfully used in precast work and occasionally in general construction. One or more vibrators are moved from bracket to bracket over the form as placing progresses. This method should be used with extreme caution, and only with units having low amplitude and high frequency.

CHAPTER 7—RECOMMENDED VIBRATION PRACTICES FOR GENERAL CONSTRUCTION

After proper vibration equipment has been selected (see Chapter 5), it should be operated by conscientious, well-trained operators. The vibrator operator should have developed, through experience, the ability to determine the time necessary for the vibrator to remain in the concrete to insure proper consolidation. By a systematic review of the operator's previous work, the operator and supervisor should be able to determine the vibrator spacing and the vibration time needed to produce dense concrete without segregation.

Internal vibration is generally best suited for ordinary construction, provided the section is large enough for the vibrator to be effectively used. However, external vibration or consolidation aids may be needed to supplement internal vibration in areas congested with reinforcement or otherwise inaccessible (See Chapter 17). In many thin sections, especially in precast work and slabs, external vibration should be the primary method of consolidation.

7.1—Procedure for internal vibration

Concrete should be deposited in layers compatible with the work being done. In large mats and heavy pedestals, the max-

imum layer depth should be limited to 20 in. (500 mm). The depth should be nearly equal to the vibrator head length. In walls and columns, the layer depths should generally not exceed 20 in. (500 mm). The layers should be as level as possible so that the vibrator is not used to move the concrete laterally, since this could cause segregation. Fairly level surfaces can be obtained by depositing the concrete in the form at close intervals; the use of elephant trunks is frequently helpful.

Even though the concrete has been carefully deposited in the form, there are likely to be some small mounds or high spots. Some minor leveling can be accomplished by inserting the vibrator into the center of these spots to flatten them. Excessive movement should be avoided, particularly through reinforced structural elements.

After the surface is leveled, the vibrator should be inserted vertically at a uniform spacing over the entire placement area. The distance between insertions should be about $1\frac{1}{2}$ times the radius of action, and should be such that the area visibly affected by the vibrator overlaps the adjacent just-vibrated area. In slabs, a standard length vibrator should be sloped towards the vertical, or a short stubby 5-inch-long vibrator should be held vertically. Both should be kept 2 in. (50 mm) away from the bottom if the slab is a tilt-up panel and when a tilt-up panel slab has an architectural bottom face. The vibration should be sufficient to close the bottom edges of the placed concrete layers.

An alternate method that has been successfully used is as follows. The vibrator should penetrate rapidly to the bottom of the layer and at least 6 in. (150 mm) into the preceding layer. The vibrator should be manipulated in an up and down motion, generally for 5 to 15 sec, to knit the two layers together. The vibrator should then be withdrawn gradually with a series of up and down motions. The down motion should be a rapid drop to apply a force to the concrete which, in turn, increases internal pressure in the freshly placed mixture.

Rapidly extract the vibrator from the concrete when the head becomes only partially immersed in the concrete. The concrete should move back into the space vacated by the vibrator. For dry mixtures where the hole does not close during the withdrawal, sometimes reinserting the vibrator within $\frac{1}{2}$ influence radius will solve the problem; if this is not effective, the mixture or vibrator should be changed.

Thin slabs supported on beams should be vibrated in two stages: first, after beam concrete has been placed, and again when the concrete is brought to finished grade.

The vibrator exerts forces outward from the shaft. Air pockets at the same level as, or located below, the head tend to be trapped. Therefore, air pockets should be worked upward in front of the vibrator.

When the placement consists of several layers, concrete delivery should be scheduled so that each layer is placed while the preceding one is still plastic to avoid cold joints. If the underlying layer has stiffened just beyond the point where it can be penetrated by the vibrator, bond can still be obtained by thoroughly and systematically vibrating the new concrete into contact with the previously placed concrete; however, an unavoidable joint line will show on the surface when the form is removed.

7.2—Judging the adequacy of internal vibration

Presently, there is no quick and fully reliable indicator for determining the adequacy of consolidation of the freshly placed concrete. Adequacy of internal vibration is judged mainly by the surface appearance of each layer. The principal indicators of well consolidated concrete are:

1. Embedment of large aggregate. Except in architectural concrete with exposed aggregate surfaces, general batch leveling, blending of the batch perimeter with concrete previously placed, a thin film of mortar on the top surface, and cement paste showing at the junction of the concrete and form.

2. General cessation in escape of large entrapped air bubbles at the top surface. Thicker layers require more vibration time than thin layers, because it takes longer for deep-seated bubbles to make their way to the surface.

Sometimes the pitch or tone of the vibrator is a helpful guide. When an immersion vibrator is inserted in concrete, the frequency usually drops off, then increases, and finally becomes constant when the concrete is free of entrapped air. An experienced operator also learns the proper feel of a vibrator when consolidation is complete.

There is a tendency for inexperienced vibrator operators to merely flatten the batch. Complete consolidation is assured only when the other items evidencing adequate vibration are sought and attained.

7.3—Vibration of reinforcement

When the concrete cannot be reached by the vibrator, such as congested reinforcement areas, it may be helpful to vibrate exposed portions of reinforcing bars. Some engineers have suggested possible degradation in concrete-to-steel bond from vibration carried down through reinforcement to partially set concrete in the lower layers of a placement. Careful examination of hardened concrete consolidated in this manner has uncovered no grounds for such fears. When the concrete is still mobile, this vibration actually increases the concrete-to-steel bond through the removal of entrapped air and water from underneath the reinforcing bars.

A form vibrator, attached to the reinforcing steel with a suitable fitting, should be used for this purpose. Binding an immersion vibrator to a reinforcing bar may damage the vibrator.

7.4—Revibration

Revibration is the process of vibrating concrete that was vibrated some time earlier. Actually most concrete is revibrated unintentionally when, in placing successive layers of concrete, the vibrator extends down into the underlying layer (which was previously vibrated). However, the term revibration as used here refers to an intentional, systematic revibration some time after placing is completed (Vollick 1958).

Revibration can be accomplished any time the running vibrator will sink under its own weight into the concrete and liquefy it momentarily. This revibration has generally been considered to be most effective when performed just prior to the time of initial setting of the concrete for mixtures with slumps of 3 in. (75 mm) or more.

Revibration generally results in improved compressive strength of standard cylinders. The effect of revibration on

concrete-to-steel bond strength is not as clear. Revibration appears to improve bond strength for top reinforcing steels placed in high-slump concrete. Revibration may, however, severely damage bond strength for reinforcing steel in well-consolidated, low-slump concrete. Revibration is almost universally detrimental to the bond strength of bottom reinforcing steel. Overall, revibration tends to reduce the differences in bond strength caused by differences in slump and position (Altowaiji, Darwin, and Donahey 1984).

Revibration is most beneficial in the top few feet (0.5 to 1 m) of a placement, where air and water voids are most prevalent. Revibration of the tops of walls normally results in a more uniform appearance of vertical surfaces.

Revibration can be very effective in minimizing cracks at the top of doorways, arches, major boxouts, etc. The procedure is to delay additional concrete placement for 1 to 2 hr., depending upon temperature, after reaching the springline of arches or headline of doors, boxouts, or joints between column and floor, etc., to permit settlement shrinkage to occur before revibration of the materials in place and the resumption of placement.

7.5—Form vibration

The size and spacing of form vibrators should be such that the proper intensity of vibration is distributed over the desired area of form. The spacing is a function of the type and shape of the form, depth, and thickness of the concrete, force output per vibrator, workability of the mixture, and vibrating time.

The recommended approach is to start with a spacing, generally in the range of 4 to 8 ft (1.2 to 2.4 m), based on the guidelines in [Section 5.2.3](#) and previous experience. If this pattern does not produce adequate and uniform vibration, the vibrators should be relocated as necessary until proper results are obtained. Achieving optimum spacing requires knowledge of the distribution of frequency and amplitude over the form, and an understanding of the workability and compactibility of the mixture.

The frequency can readily be determined by a vibrating reed tachometer (see [Section 15.3.1](#)). However, the small amplitudes associated with form vibration have been difficult to measure in the past. Inadequate amplitudes cause poor consolidation, while excessive local amplitudes are not only wasteful of vibrator power but can also cause the concrete to roll and tumble so that it does not consolidate properly.

Moving one's hand over the form will locate areas of strong or weak vibration (high or low amplitude) or dead spots. The vibrating reed tachometer can provide slightly more reliable information; the difference in oscillation of the reed at various points gives a rough indication of the difference in amplitude.

The vibrograph makes it possible to get reliable values of the amplitude at various locations on forms vibrated externally. The frequency and wave form are also generally provided.

Concrete compacted by form vibration should be deposited in layers 10 to 15 in. (250 to 400 mm) thick. Each layer should be vibrated separately. Vibration times are considerably longer than for internal vibration, frequently as much as 2 min and as much as 30 min or more in some deep sections.

Another procedure which has given good results in precast work involves continuously placing ribbons of concrete 2 to 4 in. (50 to 100 mm) thick, accompanied by continuous vibration. It can produce surfaces nearly free of bugholes.

It is desirable to be able to vary the frequency and amplitude of the vibrators. On electrically driven external vibrators, amplitudes can be adjusted to different fixed values quite readily. The frequency of air-driven external vibrators

can be adjusted by varying the air pressure, while the amplitude can be altered by changing the eccentric mass.

Since most of the movement imparted by form vibrators is perpendicular to the plane of the form, the form tends to act as a vibrating membrane, with an oil-can effect. This is particularly true if the vibration is of the high-amplitude type, and the plate is too thin or lacks adequate stiffeners. This in-and-out movement can cause the forms to pump air into the

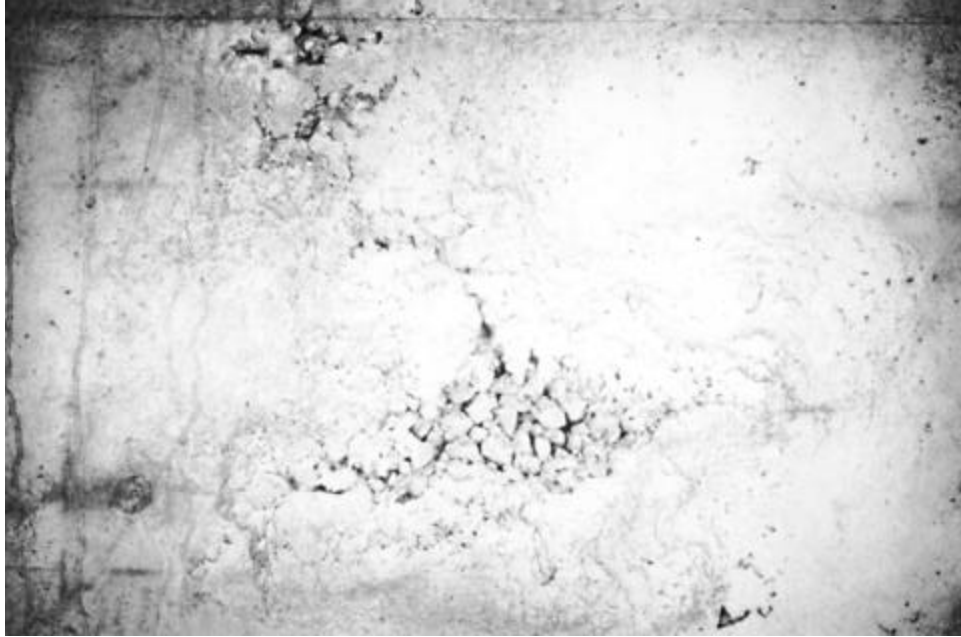


Fig. 7.6.1(a)—Honeycomb



Fig. 7.6.1(b)—Haphazard procedure may result in mortar accumulation at the surface and leave rock pockets below, particularly at batch perimeters

concrete, especially in the top few feet (0.5 to 1 m) of a wall or column lift, creating a gap between the concrete and the form. Here there are no subsequent layers of concrete to assist in closing the gap. It is therefore often advisable to use an internal vibrator in this region.

Form vibration during stripping is sometimes beneficial. The minute movement of the entire form surface helps to loosen it from the concrete and permit easy removal without damage to the concrete surface.

7.6—Consequences of improper vibration

The most serious defects resulting from undervibration are honeycomb, excessive entrapped air voids (bugholes), sand streaks, subsidence cracking, and placement lines.

7.6.1 Honeycomb—Honeycomb occurs [see Fig. 7.6.1(a)] when the mortar does not fill the space between the coarse aggregate particles. The presence of honeycomb indicates that the first stage of consolidation (see Section 4.2) has not been completed at these locations. When it shows on the surface, it is necessary to chip out the area and make a repair. Such repairs should be kept to a minimum, mainly because they mar the appearance and reduce the concrete strength. Honeycomb is generally caused by using improper or faulty vibrators, improper placement procedures, poor vibration procedures, inappropriate concrete mixtures, or congested reinforcement. Unsystematic insertions of internal vibrators at haphazard angles are likely to cause an accumulation of mortar at the top surface, while the lower portion of the layer may be undervibrated [Fig. 7.6.1(b)].

Guidance on proper placing techniques to minimize separation of coarse aggregate from mortar can be obtained from Chapter 9 of *ACI Manual of Concrete Inspection*, SP-2.

Concrete properties contributing to honeycomb are insufficient paste to fill the voids between the aggregate, improper ratio of fine to total aggregate, poor aggregate grading, or

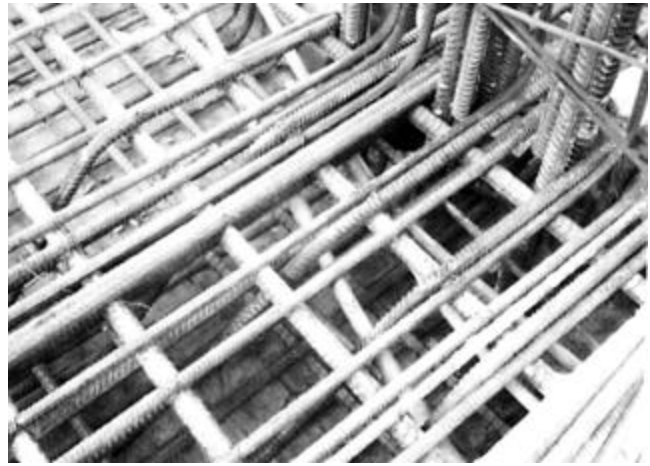


Fig. 7.6.1(c)—Poorly designed, congested reinforcement which will make good consolidation extremely difficult

improper slump for the placing conditions. Insufficient clearance between the reinforcing steel is an important cause of honeycomb [see Fig. 7.6.1(c)]. In establishing steel spacing, both the designer and builder must keep in mind that the concrete must be consolidated.

7.6.2 Excessive entrapped-air voids—Concrete that is free of honeycomb still contains entrapped air voids because complete removal of entrapped air is rarely feasible (See Section 4.2). The amount of entrapped air remaining in the concrete after vibration is largely a function of the vibratory equipment and procedure, but it is also affected by concrete mixture constituents, the properties of the concrete mixture, location in the placement, and other factors (Samuelsson 1970). When proper equipment or procedures are not used, or other unfavorable conditions occur, the entrapped-air content will be high and surface voids (commonly called bugholes) are likely to be excessive (see Fig. 7.6.2).



Fig. 7.6.2—Excessive air voids on formed surface

To reduce air voids in concrete surfaces, the distance between internal vibrator insertions should be reduced, and the time at each insertion increased. Use of a more powerful vibrator may help for some situations. Also there should be a row of insertions close to the form, but without touching it. When form contact is almost unavoidable, the vibrator should be rubber tipped; even then, any such contact should be avoided if possible because this may mar the form and disfigure the concrete surface. It is critical that the locations of vibrator insertions be such that zones of influence overlap.

Form coatings of high viscosity or those that are applied in overly thick applications tend to hold air bubbles and should be avoided.

Form vibrators tend to draw mortar to the form, and when used in combination with internal vibrators have proved effective in reducing the size and number of air voids on the surface.

For difficult conditions and when the concrete appearance is quite important, spading next to the form has been helpful in reducing air voids.

It is nearly impossible to eliminate air voids from inwardly sloping formed surfaces, and designers should recognize this fact. However, these voids can be minimized if sticky, oversanded mixtures are avoided, the concrete is deposited in shallow layers of 1 ft. (0.3 m) or less, and the vibrator is inserted as closely as possible to the form. By attaching an external vibrator to the sloping form and reducing the layer thickness to 6 in. (150 mm), voids can be considerably reduced.

7.6.3 Sand streaking—Sand streaking is caused by heavy bleeding and mortar loss along the form, resulting from the character and proportions of the materials and method of depositing the concrete (see Fig. 7.6.3). Harsh, wet mixtures that are deficient in cement and contain poorly graded aggregates—particularly those deficient in the No. 50 to 100 (300

to 150 μ m) and minus No. 100 (150 μ m) fractions—may cause sand streaking, as well as other problems. Dropping concrete through reinforcing steel and depositing it in thick lifts without adequate vibration may also cause streaking, as well as honeycomb. Another cause of sand streaking is form



Fig. 7.6.3—Sand streaking caused by heavy bleeding along form



Fig. 7.6.4—"Pour" lines

Table 12.1—Consolidation methods for precast concrete products

Products	Mix Classification (Section 12.1)	Forming material	Conveying and placing method	Consolidation method
Concrete pipe	a to d	Steel	Pumping, conveyors, or bucket (thin layers)	Tamping; internal or external vibration; cen- trifugation; vacuum; pressure
Concrete piles and poles	c, d	Steel	Pumped, or conveyed by mixer trucks	Centrifugation; internal or external, high fre- quency, low amplitude vibration; roller packed
Concrete block	b	Steel	Machine hopper	Low frequency, high amplitude vibration plus pressure
Slab and beam sections	b, c	Steel	Traveling hopper, mixer trucks, belt conveyors	External vibration with or without roller compactions; internal vibration with surface vibrating screed
Wall panels	a to c	Reinforced concrete, steel, or wood	Buckets and belt conveyors (continuous ribbon feed)	Tampers; internal and external vibration

vibrators that are attached to leaky forms that have a pump-
ing action with a resulting loss of fines or an indrawing of air
at the joints.

7.6.4 Placement lines—Placement lines are dark lines (see
Fig. 7.6.4) on the formed surface at the boundary between
adjacent batches of concrete. Generally, they indicate that
the vibrator was not lowered far enough to penetrate the lay-
er below the one being vibrated.

7.6.5 Cold joints—Delays in concreting can result in cold
joints. To avoid cold joints, placing should be resumed sub-
stantially before the surface hardens. For unusually long de-
lays during concreting, the concrete should be kept live by
periodically re-vibrating it. Concrete should be vibrated at
approximately 15-min intervals or less depending upon job
conditions. However, concrete should not be overvibrated to
the point of causing segregation. Furthermore, should the
concrete approach time of initial setting, vibration should be
discontinued and the concrete should be allowed to harden.
A cold joint will result and suitable surface preparation mea-
sures should be applied.

7.6.6 Subsidence cracking—Subsidence cracking results
from the development of tension when the concrete mechan-
ically settles at or near initial setting time. To eliminate this
type of cracking, the concrete should be revibrated at the lat-
est time at which the vibrator will sink into the concrete un-
der its own mass.

7.6.7—Undervibration is far more common than overvi-
bration. Normal weight concretes that are well proportioned
and have adequate consistency are not readily susceptible to
overvibration. Consequently, if there is any doubt as to the
adequacy of consolidation, it should be resolved by addition-
al vibration.

7.6.8—Overvibration can occur if, due to careless opera-
tion or use of grossly oversized equipment, vibration is many
times the recommended amount. This overvibration may re-
sult in:

a. *Segregation*—The mechanics of segregation come into
play when the forces of gravity and vibration are given suf-
ficient time to interact. With excessive vibration time, the
cohesive forces within the concrete are overcome by gravity
and vibration causes the heavier aggregates in the mixture to
settle and the lighter aggregates to work upward borne by the
paste matrix. Examination during or after this type of place-
ment will show a layer of laitance, a layer of mortar contain-

ing a minor proportion of large aggregate, and an
accumulation of large aggregate in the bottom of the place-
ment layer. This condition is more likely with wet mixtures
with large differences in the densities of the aggregates and
the mortar and when mixtures having too high a proportion
of mortar to coarse aggregate. Lightweight aggregate is a
problem all its own unrelated to mortar proportion. Proper
control of consistency will minimize the problem.

b. *Sand streaks*—They are most likely with harsh, lean mix-
tures and with concrete moved horizontally with the vibrator.

c. *Loss of entrained air in air-entrained concrete*—This
can reduce the concrete's resistance to cycles of freezing and
thawing. The problem generally occurs in mixtures with ex-
cessive water contents. If the concrete originally contained
the amount of entrained air recommended by ACI Commit-
tee 211 (see Chapter 18.1) and the slump is in the proper
range, serious loss of entrained air is highly unlikely. How-
ever, too many insertions of the vibrator too close together in
concrete can cause a coalescing of the entrained-air system,
which may cause a reduction in freeze-thaw durability.

d. *Excessive form deflections or form damage*—These are
most likely with external vibration.

e. *Form failure*—Excessive internal pressures that may
cause form failure can occur by allowing the vibrator to be
immersed too long in the concrete at the same location. Pres-
sure caused by excessive depth (deeper than the designed
rate of rise per hour) of fresh concrete, augmented by the dy-
namic forces of prolonged vibration, may cause the form to
fail instantaneously.

CHAPTER 8—STRUCTURAL CONCRETE

8.1—Design and detailing prerequisites

In designing structural members and detailing formwork
and reinforcement, consideration should be given to deposit-
ing the freshly mixed concrete as closely as possible to its fi-
nal position in such a way that segregation, honeycombing,
and other surface and internal imperfections are minimized.
Also, the method of consolidation should be carefully con-
sidered when detailing reinforcement and formwork. For ex-
ample, for internal vibration, openings in the reinforcement
must be provided to allow insertion of vibrators. Typically,
4 by 6-in. (100 by 150-mm) openings at 24-in. (600-mm)
centers are required.

These items require that special attention be directed to member size, reinforcing steel size, location, spacing, and other factors that influence the placing and consolidation of concrete. This is particularly true in structures designed for seismic loads, where the reinforcement often becomes extremely congested and effective concrete consolidation using conventional mixtures and procedures becomes impossible.

The designer should communicate with the constructor during the early structural design. Problem areas should be recognized in time to take appropriate remedial measures such as staggering splices, bundling reinforcing steel, modifying stirrup spacing, and increasing section size. When conditions contributing to substandard consolidation exist, one or more of the following actions should be taken: redesign the member, redesign the reinforcing steel, modify the mixture, utilize mock-up tests to develop a procedure, and alert the constructor to critical conditions.

The placing of concrete in congested areas is discussed in more detail in [Chapter 17](#).

8.2—Mixture requirements

Structural concrete mixtures should be proportioned to give the placeability, durability, strength, and other properties required with proper regard to placement conditions. The concrete should work readily into the form corners and around reinforcement by the consolidation methods employed, without segregation or excessive free water collecting on the surface. Some guidance on proportioning may be found in [Chapter 2](#), and ACI 301 covers this subject in detail. In areas of congested reinforcement, the procedures in [Chapter 17](#) should be considered. Also, consideration should be given to using mechanical connections for the reinforcement to minimize congestion.

A 3-in. (75-mm) slump is normally ample for properly vibrated structural concrete in forms. What may be regarded as a need for higher slump concrete in many quarters is better satisfied by more thorough vibration. Actually, concrete for heavy structural members can often be satisfactorily placed at a 2 in. (50 mm) maximum slump when effectively vibrated.

In those areas where thorough vibration cannot be achieved due to congested reinforcement or other obstructions, it may be desirable to increase the slump by using admixtures to produce a flowing concrete that can be more effectively consolidated (ACI 309.3R). However, it is important to note that the use of flowing concrete does not preclude the need for vibration.

8.3—Internal vibration

For most structural concrete, vibration is most effectively performed by means of standard immersion vibrators meeting the guidelines in [Table 5.1.5](#). It is important that the vibrator selected be suitable for the mixture and placing conditions.

The recommended procedure for internal vibration is described in [Section 7.1](#). In walls and beams, two vibrators should generally be used, one for leveling the mixture immediately after placement and the other for further consolidation. On larger and more critical jobs, a third unit, which may be less powerful than the other two, may be useful. It should be

used in a row of closely spaced insertions within a few inches (several centimeters) of the form, and also in the top layer of the placement, to assist air bubbles to rise and escape.

Slabs placed monolithically with joists or beams should be constructed in the following manner: all joists and beams should be placed and vibrated before the slab itself. A time interval of about an hour will permit settlement and consequent bleeding to take place in these elements prior to placing the concrete in the slab section. The slab concrete should be placed and vibrated prior to the beam concrete taking its initial set. Vibrators should penetrate through the slab into the previously placed beam concrete to consolidate and bond the structural elements.

8.4—Form vibration

Form vibration is suitable for many thin sections and is a useful supplement to internal vibration at locations where steel is unusually congested, where concrete cannot be directly placed but must flow into position, or where an internal vibrator cannot be inserted. However, form vibration can result in form pressures substantially higher than normal, and particular consideration should be given to formwork design.

Procedures for form vibration are described in [Section 7.5](#). In any use of form vibration, it is important to avoid excessive vibration at any given location. The vibrators should be moved, as necessary, to keep them operating just below the top surface of the concrete, not on unfilled areas of forms.

8.5—Tunnel

Form vibrators are used for concrete consolidation in tunnel linings. Frequently, form vibration is supplemented by immersion vibrators that are used behind the form or through access windows in the form. Tunnel-lining concrete is most commonly placed by pumping, with pump lines positioned in the sidewalls and crown. It is important to have a workable yet cohesive mixture that will respond well to vibration. The slump should be about 5 in. (130 mm) at the discharge end of the pump line.

When the level of concrete behind the form reaches the crown, an advancing slope of fresh concrete is produced. This advancing slope will generally vary from $2\frac{1}{2}$ to 1 to as much as 5 to 1, horizontal to vertical. Form vibrators should be operated within a few feet (about one meter) of the advancing slope and should be frequently moved forward horizontally. Special attention should be given to form vibration in the crown so that concrete that has been pumped into the highest points within the form is not drawn down by vibration. As the placement proceeds, the withdrawal of the pump line and position and timing of vibration must insure maximum filling of the form.

CHAPTER 9—MASS CONCRETE

Mass concrete is defined as any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking. To reduce the heat rise and to achieve economy, low cement contents and large aggregates are used and low slumps are

maintained. These measures generally require special attention in consolidation.

9.1—Mixture requirements

Proper proportioning and optimum use of chemical admixtures, fly ash, and slag in mass concrete facilitate proper consolidation. Refer to ACI 211.1 for information on mix-

ture proportioning. Additional information on mass concrete is found in ACI 207.1R.

9.2—Vibration equipment

Mass concrete containing aggregate larger than $1\frac{1}{2}$ in. (38 mm) and low cement contents presents a unique vibration problem when low slump consistencies are used. This



Fig. 9.4(a)—Stepped construction used for mass concrete construction (Photo courtesy U.S. Bureau of Reclamation)



Fig. 9.4(b)—Flattening a pile of mass concrete just deposited in form

condition requires that powerful equipment meeting the requirements of **Group 5** in **Table 5.1.5** be available for proper consolidation. Pneumatically driven vibrators are generally used in the United States. The air supply must be ample and the force at the vibrator must be sufficient for adequate consolidation. In heavily reinforced areas, vibrators with small diameters may be needed to penetrate between the bars and achieve proper consolidation.

9.3—Forms

For economy of forms and better control of temperature, mass concrete is placed in fairly shallow lifts—usually 5 to 10 ft. (1.5 to 3.0 m) thick. In addition to normal form requirements (see **Chapter 6**), forms for mass concrete are often dependent on anchors embedded in concrete for their strength and security of position. Embedment depth for these anchors should provide anchorage sufficient to withstand the impact of fast dumping from high-line or gantry buckets as well as the ordinary concrete pressures during vibration.

9.4—Vibration practices

The lifts should be built up with multiple layers 12 to 20 in. (300 to 500 mm) thick, depending on the aggregate size. Such lifts can be reliably consolidated with some penetration of the vibrator into lower layers. Heavily reinforced sections may need thinner layers and proper attention to insure the encasement of reinforcement by concrete.

Each layer is constructed in strips 6 to 12 ft (1.8 to 3.6 m) wide. The forward edge of each upper layer should be held back 4 to 5 ft (1.2 to 1.5 m) from the one below so that it will not move when vibrating the adjacent strip of lower-layer batches placed along the edge. This procedure produces a stair-step effect of the layers [see **Fig. 9.4(a)**]. The placement

is thus completed to full thickness and area with minimum surface exposure. This practice minimizes warming of pre-cooled concrete and cold joint problems between layers in warm weather. It also makes the placement easier in wet weather. Details for manufacture and placement of mass concrete may be found elsewhere (*U.S. Bureau of Reclamation Concrete Manual*, 1981; ACI 207.1R).

For effective consolidation of mass concrete, the vibrator crew should follow a systematic procedure. The crew should work closely together and move as a unit, rather than each operator working separately with widely spaced, random insertions. The vibrators should be inserted nearly vertically into the tops of the deposited piles at fairly uniform spacings and then reinserted as necessary to flatten the pile to the proper depth and spread it to the area it should occupy [see **Fig. 9.4(b)**]. Then the subsequent placements should be systematically vibrated with the vibrator penetrating the full depth of the layer and into the preceding layer, but staying away from the forward edges [see **Fig. 9.4(c)**]. The edges in contact with the previous strip and previous batch should be very thoroughly knitted together. Each vibrator operator should have his particular area of attention.

Vibration at each point should continue until entrapped air ceases to escape. Depending on mixture and slump, this time will usually range from 10 to 15 sec. The insertions must be spaced and timed to achieve thorough consolidation, not only near the surface but for the full depth of the layer and below it.

The completed top surface of the block should be left fairly even and free of footprints and vibrator holes, to facilitate the subsequent joint cleanup. The final vibration should be done by a vibrator operator on plywood snowshoes using a small vibrator if necessary. When consolidation is complet-



Fig. 9.4(c)—Systematic vibration of concrete layer

ed, the top of the coarse aggregate should be approximately at the level of the concrete surface.

The amount of concrete that can be handled by one vibrator will depend on the capability of the vibrator, the experience and diligence of the operator, and the response to vibration of the particular concrete mixture being used. Under optimum conditions, an efficient crew may handle as much as 50 yd³ (40 m³) per hr per vibrator. Around embedded items and in complicated formwork, the amount handled might be less than half this amount.

In Europe, Japan, and Canada, successful use has been made of gang vibrators using bulldozers, cranes, and hydraulic hoists. One bulldozer spreads and levels the concrete ready for consolidation. This is followed by systematic consolidation across the freshly spread concrete by three or more vibrators mounted on a frame. Successful use of this procedure requires an open form with a minimum of form ties. When a bulldozer is used to manipulate the frame, care is required in turning so that the tracks of the dozer do not dig into the concrete.

9.5—Roller-compacted concrete

Mass concrete can be compacted with vibratory rollers. Roller-compacted concrete (RCC) is a concrete of zero slump consistency that is transported, placed, and compacted in horizontal layers using the same equipment that is used for highway construction and earth and rockfill construction. Since the consolidation phase of RCC construction is performed by equipment of the sort used in earthwork, the soils term *compaction* has been used in place of the concrete term *consolidation*. Detailed information on RCC can be found in ACI 207.5R.

Roller-compacted concrete placed in the United States is generally placed and spread in 8 to 12-in. (200 to 300-mm) layers, although layers up to 3 ft. (1 m) thick have been used in some applications. For layers thicker than 12 in. (300 mm), the concrete should be deposited and spread in several thin layers prior to compaction. In open areas, layers are compacted by smooth-drum vibratory rollers with a static linear mass of 1200 to 3000 lb/ft. (1800 to 4500 kg/m) of drum width. In some applications, finish rolling has been accomplished with pneumatic-tired rollers with a static mass of up to 26 tons (24,000 kg). In tight areas and areas adjacent to walls and other obstructions, smaller walk-behind rollers and mechanical tampers can be used to compact the RCC. When using this equipment, care should be taken to place the RCC in thinner layers to assure compaction. Placement and rolling is generally done on horizontal layers. However, RCC has been placed and compacted on moderate slopes where a winch line has been used to assist the travel of the roller on the slope.

Generally, for richer and more plastic mixtures, the first pass by the roller is in the static mode (no vibration), followed by repeated passes in the vibratory mode. A delayed finish rolling approximately 1 hr after initial compaction has been effective in reducing surface cracking. Operators should insure a minimum of 6 in. (150 mm) overlap between adjacent rolling lanes and at the end of each run. Careful attention should be given to compaction of the joint along placing lanes, particularly if the concrete in the previous lane

has reached its time of initial setting. This has been achieved by rolling the edges of lanes on a 2-to-1 slope or cutting back a vertical edge into well-compacted concrete with a grader.

Selection of vibratory rollers is not yet fully understood and equipment selection should be established through field-test procedures. Vibratory rollers generally fall under two categories:

1. *High-frequency, low-amplitude rollers*—1800 to 3200 vibrations per minute (30 to 50 Hz), 0.015 to 0.03 in. (0.38 to 0.75 mm)—are used for asphalt compaction

2. *Lower-frequency, higher-amplitude rollers*—1200 to 1800 vibrations per minute (20 to 30 Hz), 0.03 to 0.06 in. (0.75 to 1.5 mm)—are used in earth and rockfill compaction

Construction parameters, such as lift thickness, and characteristics of the concrete mixture, nominal maximum size of aggregate and water content, may influence selection of rollers.

Special care should be taken in proportioning the RCC mixture and in placing techniques to avoid segregation or contamination over the previously placed lift to assure a well-bonded, low permeability lift joint. When freshly mixed RCC concrete is placed on a hardened lift surface, the surface should be clean, and a thin layer of mortar or several inches (± 100 mm) of a more plastic bedding mixture should be placed on the surface before covering with the regular RCC mixture. Generally, 4 to 6 passes with a properly sized vibratory roller are sufficient to produce a dense, well-compacted concrete. However, increased lift thickness and stiffer-consistency RCC mixtures may require more passes. Field trials should be conducted to determine the number of roller passes required to achieve full compaction.

CHAPTER 10—NORMAL WEIGHT CONCRETE FLOOR SLABS

10.1—Mixture requirements

Concrete for slab construction should be proportioned to give the required placeability, finishability, abrasion resistance, strength, and durability. ACI 302.1R covers recommended procedures for floor and slab construction.

Stiffer mixtures are commonly used for durable, abrasion-resistant surfaces. These require consolidation by vibration or other effective means. Recommendations in this guide are primarily for this class of construction.

10.2—Equipment

Surface vibration is recommended for consolidating slabs up to 6 in. (150 mm) thick, provided they are unreinforced or contain only light mesh. Vibrating screeds, supported on the forms, screed boards, or rails, are the most common means. They should be low-frequency (3000 to 6000 vibrations per min [50 to 100 Hz]) and high-amplitude to minimize machine wear and provide adequate depth of consolidation without creating an objectionable layer of fines at the surface. Use of the high-frequency, low-amplitude type is acceptable when applied solely to accommodate the finishing operation. Unreinforced slabs 6 to 8 in. (150 to 200 mm) thick may be consolidated by either internal or surface vibration.

Internal vibration, using equipment described in [Table 5.1.5](#), is recommended for all slabs more than 8 in. (200 mm)



Fig. 10.6—Vacuum dewatering of concrete slab is shown just behind the floor finishing operation

thick. It is also recommended for slabs of lesser thickness that contain reinforcement or other embedments, such as conduit. Internal vibration should also be provided adjacent to load transfer devices and forms.

10.3—Structural slabs

Structural slabs that contain reinforcement and conduit and should be internally vibrated. Vibrating screeds are also used frequently to facilitate finishing; a high-frequency, low-amplitude type may be used in this case.

Often, the slab will contain projecting columns, conduit, or reinforcing bars that prevent setting forms or screed boards needed for a vibrating screed. Such floors must be screeded by hand and slumps in excess of 2 in. (50 mm) are required. At these slumps, adequate consolidation will be obtained by internal vibration and the hand-screeding and finishing operations.

10.4—Slabs on grade

The procedures described in [Chapter 11](#) should be followed on large jobs when practical. However, many floor slabs are small, odd-shaped, or on nonuniform sections so that highly mechanized procedures cannot be used. Such construction is covered by the procedures given in this chapter.

10.4.1 Internal vibration—The vibrator head should be completely immersed during vibration. For thick slabs, it will be possible to insert the vibrator vertically, while for thinner slabs it should be inserted at an angle, or even hori-

zontally. Contact of the vibrator with the subgrade should be kept to a minimum since this might contaminate the concrete with foreign material.

The use of vibrating screeds, when edge forms or screed rails can be used, will facilitate strikeoff operations after the slab has been consolidated by internal vibration. By using a vibrating screed, one can use concrete of lower slump.

10.4.2 Surface vibration—Slumps in the range of 1 to 2 in. (25 to 50 mm) are generally recommended for concrete consolidated by vibrating screeds. For slumps in excess of 3 in. (75 mm) vibrating screeds should be used with care, since such concrete will have an accumulation of mortar on the finished surface after vibration.

Vibrating screeds strike off and straightedge the concrete in addition to providing consolidation. To perform significant consolidation, the leading edge of the shoe must be at an angle to the surface and the proper surcharge (height of uncompacted concrete required to produce a finished surface at the proper elevation) must be carried in front of the leading straightedge.

When it is impractical to set screed boards or forms for vibrating screeds or other surface vibrators, the slump will have to be increased to between 3 and 4 in. (75 and 100 mm) and the primary consolidation obtained through the straightedging and finishing operations. Spading or internal vibration will be required to consolidate concrete adequately

around reinforcing steel, load-transfer devices, keyways, and the edges of forms.

10.5—Heavy-duty industrial floors

The wearing surface of heavy-duty industrial floors should be of a high-quality concrete. For information regarding the various floor classifications and requirements, refer to Table 1.1 in ACI 301.1R. Many industrial floors are placed as two courses, with conventional concrete in the bottom course and a higher quality concrete in the top course. The top course should preferably be placed before the bottom course has attained final set. The use of two course floor systems provides economy and a more efficient use of materials.

The top surface should be struck off slightly above the finish grade. The wearing course should then be compacted by rolling, tamping, or other surface vibration. The use of a power-disc float with hammers will provide additional consolidation of the near-surface region. In these concretes, the disc float must be used soon after the screeding operation if sufficient mortar cannot be brought to the surface to adequately fill the surface voids.

Chemical admixtures may be used to increase the workability of mixtures to make consolidation easier.

10.6—Vacuum dewatering

The vacuum process is a method of improving the concrete quality near the surface by removing part of the mixing water after the concrete has been placed; however, some reconsolidation is involved (see Fig. 10.6). Mats are applied to the surface after the normal consolidation has been completed and they are connected to vacuum pumps. The suction applied by the pumps and the atmospheric pressure (a consolidating force), acting simultaneously on the mats, remove water and entrapped air from the region near the surface and close up the spaces formerly occupied by the water.

CHAPTER 11—PAVEMENTS

Highway and airfield pavement jobs include applications such as continuously reinforced pavements and bridge decks and may use concrete at rates in excess of 500 yd³ (400 m³) per hr. Automated equipment capable of handling 1 to 2-in. (25 to 50-mm) slump concrete is generally used for placing and finishing. At the other extreme, residential developments may require less than 100 yd³ (80 m³) of concrete per day. Considerable hand-work is frequently used, necessitating slumps in the range of 2 to 4 in. 50 to 100 mm).

This guide is aimed at highway and airfield construction. The procedures described generally apply either to fixed-form or slipformed pavements. Zero-slump concrete pavements are placed by the roller compaction process as described in Section 9.5.

11.1—Mixture requirements

The concrete mixture should have adequate placeability and finishability to achieve the desired consolidation and finish. The slump should be 2 in. (50 mm) or less to keep segregation and loss of entrained air to a minimum and to maintain the quality of the concrete.

The concrete received at the placing point should be uniform. Variations in the mixture may result in segregation or inadequate consolidation, causing the pavement to have poor riding qualities and poor durability. For fiber-reinforced concrete, internal vibrators must be used at a closer spacing and for a longer period of time to obtain satisfactory results (see ACI 544.1R).

11.2—Equipment

11.2.1 Selection of equipment—All pavements should be consolidated by full-width vibration. The type of vibration—internal or surface—is determined by the slab thickness, the rate of production, consistency, and other characteristics of the concrete mixture.

Internal vibrators, usually gang-mounted spud vibrators, meeting the guideline in Table 5.1.5 should be used when pavement thicknesses are 8 in. (200 mm) or more. When equipment moves rapidly over slabs to attain high production rates, internal vibration may be needed in pavements as thin as 4 in. (100 mm). Hydraulic vibrators have increased rapidly in popularity in recent years, mainly because the frequency is adjustable and maintenance requirements are low.

Surface vibrators may be used for pavements less than 8 in. (200 mm) thick and have been successfully used for pavements up to 10 in. (250 mm) thick using greater vibrational effort. However, the production rate will be lower than that obtained with internal vibrators. Also, surface vibration in combination with striking off, screeding, and floating can bring excess fine material to the surface. This can happen as a result of improper mixture proportions or over-working the surface, or both.

The speed of the paving train controls the time of vibration, and the equipment and mixture proportions must be selected accordingly.

11.2.2 General requirements—Both surface and internal vibrators should be controlled by an automatic on-off switch that operates the vibrators simultaneously, and only when the machine is in forward motion.

The ability to vary frequency is desirable to permit adjustment for the job conditions and materials being used.

Standby vibrator units should be available for replacement or if needed for additional vibration.

11.2.3 Internal vibrators—In addition to the usual internal vibrators described in Chapter 5, L-shaped spuds are also available for pavement construction. The latter are especially adapted for consolidating the thinner slabs and for operating above the mesh in reinforced pavements.

The vibrators are usually gang-mounted on a horizontal frame (see Fig. 11.2.3) that should be located immediately in front of the first screed or extrusion plate. The frame should be adjustable forward and backward to compensate for differences in concrete consistency from job to job.

The frame should be capable of spacing 10 to 14 vibrators over a 24 ft (7.3 m) paving width. It should also be capable of vertical movement so that the spuds can be completely withdrawn from the concrete or lowered to the exact position in the concrete required for optimum vibration.



Fig. 11.2.3—Gang-mounted spud vibrators for consolidating pavement concrete



Fig. 11.2.4(a)—Pan-type surface vibrator for pavement construction



Fig. 11.2.4(b)—Older screeds with trucks permitting cam-like action to raise screed to clear concrete surface when moving for second pass

The vibrators should be capable of angular adjustment that can be maintained during vibration.

The vibrator frequency should be adjustable between 8000 and 12,000 vibrations per min (130 and 200 Hz). The frequency from vibrator to vibrator should be uniform.

Hand-held immersion vibrators of the type used in consolidating structural concrete may be useful along forms or in irregular areas.

11.2.4 Surface vibrators—Three types of surface vibrators are used in concrete pavement construction—vibratory screed, vibratory pan, and vibratory-roller screed (see [Section 5.3](#)).

The vibratory screed is a dual-purpose unit that consolidates the concrete and strikes off the surface. The ends of the screed generally are not equipped with trucks (wheel assemblies) [Fig. 11.2.4(a)]. Older equipment may have trucks [Fig. 11.2.4(b)] with a cam-like action, so that the screed may be raised clear of the concrete surface when moving it back for a second pass. Small screeds may be lifted by hand. A unit is normally required for each lane of width. Vibratory screeds should be capable of varying the frequency from 3000 to 8000 vibrations per min (50 to 130 Hz).

The vibratory pan is the only surface vibrator used strictly for consolidation. The pan should be mounted on a horizontal frame capable of raising it clear of the concrete or holding it at the surface as desired. The pan vibrator should be adjustable in frequency from 3000 to 6000 vibrations per min (50 and 100 Hz).

The final type of surface vibrator is the vibratory-roller screed, which strikes off as well as consolidates. The frequency should be adjustable; the range for the most widely used current model is 100 to 400 vibrations per min (2 to 7 Hz). This equipment requires a concrete slump of more than 2 in. (50 mm) and its use should be limited to irregular areas and hand placements.

11.3—Vibration procedures

11.3.1 Internal vibrations using gang-mounted vibrators—The centrifugal force and vibrator spacing should be based upon the aggregate to be used, mixture characteristics, rate of concrete delivery, method of reinforcement placement, and paver speed. Vibrators with a centrifugal force near the low end of the range shown in [Group 3 in Table 5.1.5](#) should be used for mixtures with small coarse aggregates and high fine aggregate contents. Normally, the trial spacing should be 20 to 30 in. (500 to 750 mm). The lower the centrifugal force and the shallower the slab, the closer the spacing. The location of the outside vibrators is critical, especially in slipform paving.

When nonuniformity or mortar streaking occurs in vibrator paths while operating at normal paving speeds, the vibrators should be lowered in the concrete, their angularity changed, the frequency increased or decreased, the amplitude changed (usually by changing the eccentric mass), or additional vibrators added until the streaking is eliminated. Proper consolidation is generally achieved when the concrete surface has a uniform texture and sheen, with coarse-aggregate particles barely visible on or immediately below the surface.

For pavements less than 10 in. (250 mm) thick, the vibrators should be operated parallel with, or at a slight angle to, the subbase. For thicker nonreinforced pavements, the vibrators should be close to the vertical, with the vibrator tip preferably about 2 in. (50 mm) from the subbase, and the top of the vibrator a few inches below the pavement surface.

A 4 to 6-in. (100 to 150-mm) surcharge of concrete should be carried over the vibrators during the placing operation. Greater surcharge loads are likely to cause surging behind the screed or extrusion plate and prevent full release of entrapped air.

For reinforced pavement with thicknesses less than 10 in. (250 mm), the vibrators should be parallel with the subbase above and as near as practical to the reinforcement but at least two vibrator diameters below the surface. When the reinforcement is close to the surface, the concrete should be placed in multiple passes to permit consolidation. If inadequate consolidation is discovered at the bottom of the slab under the steel, space the vibrators closer together, increase the vibratory effort, or decrease the paver speed. Since it is common practice to attach the vibratory unit to the equipment carrying the first transverse screed, the proper adjustment of the vibrators will depend on the forward speed of this equipment.

Reinforced slabs in which the reinforcement is placed by vibration after full-depth concrete placement require initial consolidation prior to steel placement. In continuously reinforced pavements where the steel is placed on chairs prior to concrete placement, care should be taken to insure that the concrete below the reinforcing steel is receiving adequate consolidation. For reinforcement placed with a mesh depressor, less vibration will normally be required than for mesh placed on chairs or for concrete placed in two courses. For reinforced slabs placed in two courses, the vibrators should be used in both courses.

Olsen, Winn, and Ledbetter et al. (1984) provide additional information on consolidation of concrete pavements.

11.3.2 Surface vibration

11.3.2.1 The vibratory-pan unit should be positioned behind the surface strikeoff equipment. The vibration frequency should be set in accordance with the forward speed of the equipment on which it is mounted. A surcharge should not be allowed to build up in front of the pan because it will dampen the vibrations. An internal spud vibrator may assist in consolidating concrete along each form.

11.3.2.2 It is usually advisable to make two passes of the screed or roller. The first strikes off and consolidates the concrete, and the second provides the surface finish. Maximum frequency should be used on the first pass and a reduced frequency on the second. In this case, surface appearance is not a satisfactory criterion of the adequacy of consolidation. An understanding of the effectiveness of consolidation below the surface is required.

11.3.3 Manual vibration—Hand-held immersion vibrators should be used adjacent to all headers (bulkheads) and joint assemblies, unless a vibratory dowel installer or full-width internal vibration is used. They should also be used in other areas where gang-mounted vibrators are not practicable. The vibrator head should be completely immersed in as near a ver-

tical position as practicable to avoid segregation and mortar streaking. The concrete should be vibrated to the required depth by systematic vibration of overlapping areas. The insertion spacing should generally be 20 to 30 in. (500 to 750 mm) or about $1\frac{1}{2}$ times the effective radius of action. It is better to space the insertions too closely than too far apart.

The vibrator should operate in one location until the concrete is consolidated thoroughly, then it should be withdrawn slowly to insure closing the hole resulting from the vibrator insertion. The length of time to effect thorough consolidation will vary with the concrete workability and the centrifugal force of the vibrator. Vibration time may be as short as 5 sec or as long as 20 sec per point of application.

11.4—Special precautions

When placing air entrained concrete, air content of the consolidated concrete in place should be checked. Certain methods of consolidating and finishing pavements will effect the characteristics of the air void system. When air entrainment is required for frost resistance, the air void parameters in the hardened concrete should be verified. If the air content falls below the specified level, changes should be made in the vibrating procedures or in the amount or type of air-entraining admixture being used. The depth and location of reinforcing steel should be checked behind the vibrators to assure that the reinforcement has not been dislocated.

When fixed forms are used, the pavement edge should be examined after form removal to determine the effectiveness of the vibrators. If honeycomb is observed, one or more of the following changes should be made to prevent its recurrence: (1) position vibrators closer to the forms, (2) increase frequency or amplitude of the vibrators, or (3) reduce the forward speed of the paving equipment.

In slipform paving, the equipment should move forward as continuously as possible, especially in warm weather. Delays, and starting and stopping the paver, may produce tearing of the surface and edges of already consolidated concrete. Tearing can extend to a depth of 6 to 8 inches (150 to 200 mm) and result in a loss of consolidation. The condition is caused by the development of excessive friction between the top or side form of the paver and concrete. Factors that can contribute to tearing include thickness of the slab, use of concrete with too low a slump, concrete temperature, wind and humidity, mixture proportions, particle shape of the aggregates, rate of slump loss, and adjustment and operation of the slipform paver. Once tearing has occurred, the only means of restoring integrity to the concrete is to use immersion vibrators and revibrate the affected area. If tearing is near or on the edge, installation of side forms may be required to retain the concrete during vibration.

Cores should be taken periodically to check the adequacy of consolidation. Those taken to check pavement thickness may be suitable for this purpose. The top surface of cores should be examined to determine the thickness of the mortar layer above the coarse aggregate. Mortar thicknesses over coarse aggregate in excess of $\frac{1}{8}$ in. (3 mm) indicate overvibration or overfinishing, which can result in reduced abrasion resistance. This also indicates an over-mortared

mixture. The inspector should record locations of breakdowns, delays, or other unusual events and should request cores from these areas.

The density of fresh concrete immediately after vibration can be determined by the use of nuclear gages. These gages measure relative density, which is the plastic mass per unit volume measured in the normal manner (ASTM C 138). This can provide a useful means for indicating when the desired degree of consolidation has been achieved. Useful results can be obtained on large jobs where the cost can be justified, where testing personnel are available, the instrument is properly calibrated, and the concrete mixture is reasonably uniform.

Excessive entrapped-air voids in the cores indicate a need for additional vibration, or a change in the location or spacing of vibrators. Intrusion of subbase material into the concrete may result from internal vibrators set too low or at an incorrect angle.

Changing job conditions such as weather, rate of progress, changes in equipment, and slump may necessitate a change in the characteristics or position of the vibrators. The inspector should watch for nonuniformity behind the vibrators. Nonuniformity caused by improper use of gang vibrators has been known to produce lines of weakness that can develop into longitudinal cracks.

CHAPTER 12—PRECAST PRODUCTS

The consolidation method for precast products should be selected on the basis of the end use of the product, concrete mixture, forming material, and production technique so that the entire operation can be efficiently planned and coordinated. Table 12.1 summarizes pertinent data for some precast concrete products.

12.1—Mixture requirements

The workability of the mixture is an important consideration in selecting the consolidation method for precast work. In precast work, generally the following consistencies are used:

- a. Stiff mixtures. These are harsh, zero-slump mixtures that exhibit little cohesiveness when squeezed in the hand. Because of their low water content, moist curing is generally used to achieve adequate cement hydration.
- b. Stiff plastic mixtures. These mixtures have some cohesiveness and are slightly plastic, usually with less than 1 in. (25 mm) slump.
- c. Uniformly or gap-graded mixtures having slump in the 1- to 4-in. (25- to 100-mm) range. These mixtures are cohesive and plastic.
- d. Mixtures having over 4-in. (100-mm) slump that flow readily, and have a high potential for segregation if mechanical vibration is applied.

In precast work, it may be necessary to adjust the mixture proportions, within reasonable limits, to provide compatibility with the available precasting equipment.

12.2—Forming material

The consolidation method should be compatible with the form or mold material. Steel, wood, and reinforced concrete are



Fig. 12.4—Form vibration used in precast beam construction

generally preferred. Forms may be lined with fiberglass or other plastics to produce special surfaces. Rubber has also been used.

Care should be taken to prevent form damage during consolidation. For example, internal vibrators should have a rubber tip and contact between the vibrator and form should be avoided.

12.3—Production technique

For products that have been standardized, well developed methods are generally available. Machinery is available for manufacturing the following standardized products:

- a. Concrete pipe;
- b. Concrete block and lintels;
- c. Floor slab units;
- d. Small paving slabs (patio block, etc.);
- e. Building units such as load bearing wall panels.

Custom-built products present more difficult problems. Experience in mixture proportioning, mold design, and other factors lead to the best casting and consolidation method. The number of units to be cast should also be considered.

The information in [Chapter 5](#) should be helpful. Previous experience and experimentation are frequently employed to arrive at the final solution.

12.4—Other factors affecting choice of consolidation method

External form vibration (see [Fig. 12.4](#)) or vibrating tables are generally preferred over internal vibration in the precast industry. They give more uniform control and allow more economical techniques to be adopted in day-to-day production of similar units. When the section involves large concrete masses remote from external vibrators, supplemental internal vibration should be provided.

Tamping is an effective method of consolidating stiff concrete placed in thin layers.

Pressure vibration is suitable for stiff mixtures. Here a given concrete volume is placed in a mold and a force is applied to the top concurrent with the vibration.

The curing method may affect the choice and operation of consolidation equipment. External form vibrators that are not removable and are exposed to steam and moisture are likely to have high maintenance costs, especially if they are electrically powered.

12.5—Placing methods

The method of depositing concrete in the forms is important to consolidation. To expel the maximum amount of entrapped air and to keep the voids on formed surfaces at a minimum, vibration should be continuous during concrete placement.

Dumping concrete in intermittent heaps should be avoided. Portable mixers or mixer trucks should discharge in a continuous moving ribbon directly into the form, rather than discharging into a bucket and intermittently dumping the concrete in heaps.

When using vibrating or drop tables, a uniform concrete layer should be placed in the mold before the table is placed in operation. When shallow slabs are manufactured, the form should be completely filled before vibration starts. If the depth exceeds 12 in. (300 mm), it is best to use two or more layers. The concrete consistency and desired surface appearance will also affect the method employed; the lower the water-cement ratio, the shallower the lift that should be used.

CHAPTER 13—LIGHTWEIGHT CONCRETE

Concrete made with lightweight aggregate is used to reduce dead loads resulting in smaller structural members and foundation sizes. Lightweight concrete is also used to provide better fire resistance and to serve as insulation against sound and heat transmission.

13.1—Mixture requirements

Most commercially available lightweight coarse aggregates have a nominal maximum size of $\frac{1}{2}$ or $\frac{3}{4}$ in. (13 or 19 mm). The fine aggregate may be either normal weight or lightweight, or a combination of both, providing the concrete meets density and strength requirements.

A slump of 2 to 3 in. (50 to 75 mm) is adequate for normal construction. With higher slumps the larger pieces of lightweight aggregate may float to the top surface during vibration. Stiffer mixtures are frequently used in precast work.

Air entrainment is highly desirable in lightweight concrete. It imparts cohesiveness to the mortar so that the coarser particles have less tendency to float during vibration.

13.2—Behavior of lightweight concrete during vibration

During vibration, the entrapped air bubbles are brought to the surface through buoyancy and dissipated as for normal weight concrete. However, the lower density of the mixture results in somewhat less buoyancy for the air bubbles. It is important to allow enough vibrating time to remove the air bubbles, while noting that with lengthy vibration times much of the entrained air may be lost and some of the lightweight aggregate particles may float.

Segregation of concrete mixture components during vibration is caused by differences in their specific gravities. In normal weight concrete, the coarse aggregate is heavier than the mortar and therefore tends to sink during vibration. In lightweight concrete, the reverse is true, although the tendency for the coarse aggregate to float is less when the mortar contains lightweight fine aggregate. Dry mixtures will not segregate as rapidly under vibratory action as wet ones.

13.3—Consolidation equipment and procedures

Equipment recommended for consolidating normal-weight concrete is also suitable for lightweight concrete.

As for normal-weight concrete, lightweight concrete should be placed as closely to its final position as practicable to avoid segregation. Vibrators should not be used to move the concrete laterally. Shovels are frequently helpful in depositing or moving the concrete.

Most practices used for vibrating normal-weight concrete can be followed with lightweight concrete. However, due to the reduced buoyancy of entrapped air bubbles in lightweight concrete, the layer depths should be reduced to approximately 80 percent of those given in [Section 7.1](#). The vibrators should be inserted at close intervals and should penetrate the previously placed layer. Sufficient time, usually about 10 sec, should be given at each insertion to get adequate consolidation. Stiffer mixtures may require a few additional seconds.

On walls where surface air voids are objectionable, the following procedure is suggested. Each layer should be vibrated in the normal manner, and then revibrated immediately prior to placing the succeeding lift. If a period of about 30 min (or as long as practical) is allowed between vibration operations, this procedure can be quite effective. As an alternative to the second vibration, which may require additional vibrators, hand spading or spudding against the form surface is moderately effective.

13.4—Floors

Consolidation and finishing operations should receive particular attention when lightweight concrete is used in floor construction. While most of the recommendations in Chapter 10 are applicable, some additional precautions are helpful.

Air entrainment and minimal slump are both very desirable. These will assist in preventing the lightweight coarse aggregate particles from coming to the top surface.

Best consolidation is obtained by dragging the vibrator through the concrete in a nearly horizontal position at about the same spacing as used for vertical insertions. Dragging at a constant velocity will give more uniform vibration than jerking motions. In lieu of internal vibrators, vibrating screeds may be used for thin floors where there are no obstructions to impede their use.

Where segregation has occurred, a hand-operated grid tamper or mesh roller may be used to depress the floating lightweight coarse aggregates slightly below the top surface.

CHAPTER 14—HIGH DENSITY CONCRETE

Concrete made with high density aggregates is primarily used for radiation shielding and counterweights. For radiation shielding, it is absolutely essential that the concrete be dense, practically free of voids and cracks, and homogeneous.

14.1—Mixture requirements

Aggregates for high density concrete comprise iron products (specific gravity 7.5 to 8.0), heavy slags (specific gravity over 5.0), and hydrous or mineral ores (specific gravity 3.5 to 4.8). These materials may be used individually or in combination to obtain concrete densities from about 160 to over 380 lb/ft.³ (2600 to over 6100 kg/m³). (See ASTM C637 or C638.)

Normal mixture proportions range between 1:6 and 1:10 by mass of cement to combined fine and coarse aggregate. The water-cement ratio is usually between 0.45 and 0.65.

Settlement can generally be minimized by proper proportioning and incorporation of suitable chemical admixtures.

14.2—Placing techniques

Heavyweight concrete is fabricated by conventional mixing and placing methods, by aggregate immersion (puddling), or by preplaced aggregate construction (ACI 304.3R). Formwork should receive careful attention, because heavyweight concrete exerts considerably higher pressures on forms than normal weight concrete. Form pressure can be reduced by placing concrete in slowly rising lifts. Care must be taken to avoid excessive loads on the concrete handling equipment due to the higher density of heavyweight concrete. It is common practice to reduce concrete truck and bucket loads by half.

14.2.1 Conventional placing techniques—Conventional placement methods may be used for concrete containing high density aggregates, provided the mixture is workable and the forms are relatively free of embedded items. However, such concrete presents special problems due to the tendency of the high density aggregate particles to segregate. Segregation is greatest where the aggregates are not uniform

in grading or density, the mixture contains excessive moisture, or the slump is excessive. Concrete slump should generally be between 1.5 and 3 in. (40 and 75 mm) for high density mineral aggregate mixtures. Placement and consolidation must be closely controlled to insure uniform density and freedom from segregation.

Internal vibration is often supplemented with external vibration, but extra care must be taken when the heavy aggregates are friable and easily broken down. Vibrator frequencies used for normal-weight concrete are usually satisfactory for heavy-weight concrete. However, somewhat higher frequencies—about 11,000 vibrations per min (180 Hz)—together with shorter vibration periods have sometimes been found to reduce the tendency for segregation, especially when steel punchings or other very high density aggregates are used. The potential for overvibration is increased with the use of high density aggregates, which can result in the settlement of the heavy particles. The radius of action of a vibrator in heavy-weight concrete is less than in conventional concrete, so a closer spacing of insertions is required.

14.2.2 Special placing techniques—When segregation cannot be avoided or when embedded items or restrictions prohibit conventional placement, the preplaced or postplaced aggregate methods may be employed.

In the preplaced aggregate method (ACI 207.1R, ACI 304.1R, and 304.3R), embedments such as heavy reinforcement, pipes, and conduits may be vibrated during aggregate placement to minimize unfilled pockets. When vibration of embedded items cannot be tolerated, the aggregate may be hand placed or rodded into position. Vibration during grout pumping should be avoided except where a superior surface finish is desired. Hurd (1989) indicates that forms may be lightly vibrated near the grout surface.

Postplaced aggregate is a rarely used technique in which up to one foot (300 mm) of high density grout is placed in the form and heavy aggregate is embedded into it. The coarse aggregate is worked into place by rodding. Internal vibration should be avoided, especially where the grout contains high-density fine aggregates.

CHAPTER 15—QUALITY CONTROL AND INSPECTION

15.1—General

Good consolidation is the result of:

1. Good specifications and enforcement;
2. Good design relative to geometry and reinforcing steel;
3. Good mixture proportions;
4. Use of proper equipment, and maintenance practices to keep it in good working order;
5. Proper field procedures. Workers should understand why they are consolidating the concrete and the consequences if it is improperly done;
6. Quality control procedures implemented by the contractor;
7. Quality assurance and testing to see that proper quality control procedures are followed.

15.2—Adequacy of equipment and procedures

Concrete workability is not constant, even with the best of control. Variations in aggregate grading and in consistency due to slump loss between the mixer and form should be compensated for by slight changes in the consolidation procedure. There should be sufficient flexibility—in vibration time, vibrator spacing, and sometimes vibrator properties—to adjust to these changed conditions.

Slumps should be as low as practical for the working conditions. Properly sized vibrators in good operating condition are essential. Use of the recommended layer depth, vibrator spacings, timing, and penetration depth are also important to the quality of the final product.

Spare vibrators should be available at the point of placement to maintain production in the event of a breakdown, or when vibrators are taken out of service for routine maintenance and repair.

Mechanical consolidation equipment cannot operate properly unless adequate power is available. With electric vibrators, voltage can be expected to vary appreciably and should be regularly checked. With pneumatic vibrators, the air pressure at the vibrator should be regularly checked, either by installing an ordinary dial gage in the line, or by inserting a needle gage in the air hose.

Since internal vibrators are used in wet (conductive) locations, all electric units should be grounded to the power source. Power generators should also be grounded to maintain continuity of the grounding system. Units operating at less than 50 volts, or that are protected by an approved double insulation system, are excepted. In the United States, electric vibrators are subject to Article 250-45 of the National Electric Code (1990).

15.3—Checking equipment performance

All vibratory units should be checked prior to starting the work, and periodically during construction, to verify that they are working properly.

15.3.1 Frequency of internal vibrators—The vibrating reed tachometer (see Fig. 15.3.1) is a simple device for checking the frequency of an internal vibrator. The frequency should be occasionally determined while the vibrator is operating in air, but it is the frequency while operating in concrete that is most important and requires regular checking. The latter can be determined by holding the device against the back end of the vibrator while it is almost submerged; for a pneumatic vibrator, holding the device against the hose is equally satisfactory. This measurement should be taken just before the vibrator is withdrawn, and is always the fastest speed while it is operating in concrete. The resonant reed tachometer is a more expensive instrument that gives more accurate values of frequency.

15.3.2 Amplitude of internal vibrators—The amplitude of an internal vibrator varies linearly along the head with the maximum value occurring at the tip. The average amplitude of most internal vibrators while operating in air may be approximately computed by the formula given in Fig. A.2 in the Appendix.

With care, this device is capable of an accuracy of about 0.005 in. (0.13 mm).

The actual amplitude should also be determined by measurement. This will serve as a check on the manufacturer's data and will indicate whether the vibrator is working properly. It will also provide other useful data, for example, the maximum amplitude and the distribution of amplitude along the head. A visual-effect scale (optical wedge) may be used

for this purpose. Several vibrator firms have prepared scales on stickers which may readily be attached to the vibrator head. See Figure 15.3.2.

For flexible-shaft electric and most pneumatic vibrators, a measurement should be taken near the tip and another near the back end of the head, and these results averaged.

For the motor-in-head and pendulum vibrators, where the eccentric is near the tip, the amplitude will generally be relatively large at the tip. It will decrease rapidly until a node (point of zero amplitude) is reached near the back end, and the amplitude will increase to a relatively small value at the extreme back end. The node can be verified and located by moving one's hand over the vibrator surface. If the node is less than one-fifth of the head length away from the back end, the average amplitude may be taken as one-half the measured tip amplitude. If the node point is at a greater distance from the back end, a second measurement (probably near the back end) should be taken. The average amplitude can then be determined as the mean of the two measurements.

15.3.3 Frequency and amplitude for external vibration—

The frequency and amplitude of vibrating forms and vibrating tables should be determined at sufficient points to establish their distribution over the surface.

The frequency may be determined by a vibrating reed or resonant reed tachometer.

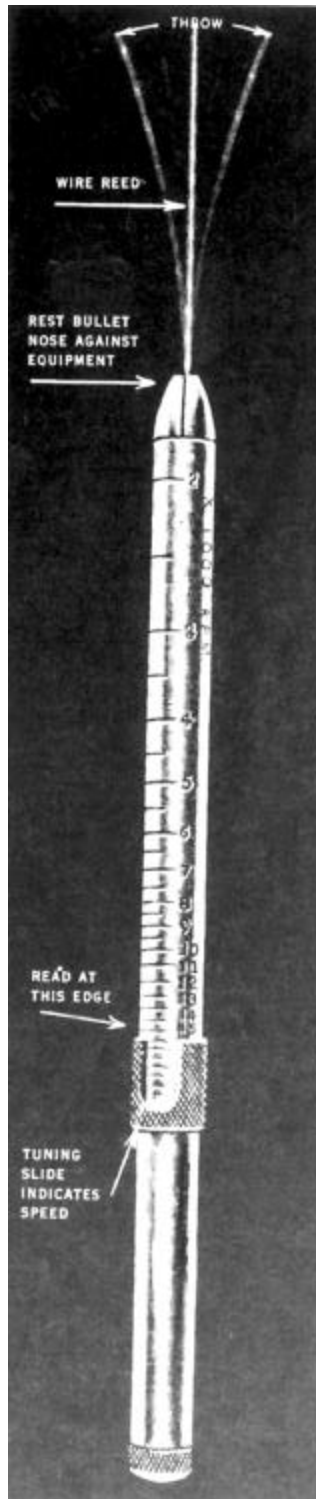
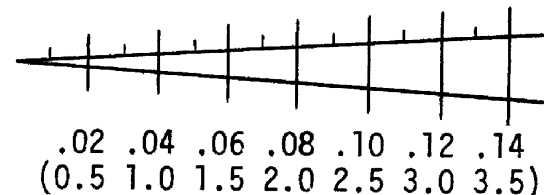
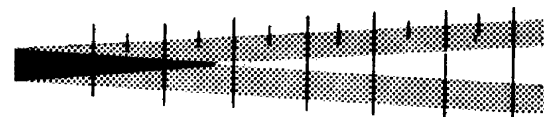


Fig. 15.3.1—Vibrating reed tachometer



Amplitude, in. (mm)

SCALE AT REST



Indicating an amplitude of
0.055 in. (1.4 mm)

SCALE DURING VIBRATION

INSTRUCTIONS FOR USE

Attach scale to vibrator head at point where amplitude is desired, with center line of "V" parallel to axis of vibrator.

With the head vibrating, a black triangle forms at the apex of the "V." The scale reading at the tip of the triangle is the peak amplitude (peak-to-peak total displacement). A hand reading glass (2 to 3x) improves the accuracy of the reading.

With care, this device is capable of an accuracy of about 0.005 in. (0.13 mm).

Fig. 15.3.2—Visual effect scale for measuring amplitude of vibrator operating in air



Fig. 15.3.3—Using vibrograph to determine amplitude and frequency of vibrating form

The amplitude may be determined by using a vibrograph. The model shown in Fig. 15.3.3 measures amplitude within an accuracy of about 0.0005 in. (0.013 mm). It also records the wave form, which is frequently of interest, and provides the frequency. It is quite portable.

CHAPTER 16—CONSOLIDATION OF TEST SPECIMENS

16.1—Strength tests

In current ASTM standards (C 31, C 192, and C 1018) for making control specimens for strength tests:

- a. Rodding is required for concrete with slumps of more than 3 in. (75 mm). Vibration is prohibited because of the danger of removing excessive entrained air and causing segregation.
- b. Either rodding or vibration is permitted for slumps in the 1 to 3 in. (25 to 75 mm) range.
- c. For slumps less than 1 in. (25 mm), vibration is required.
- d. For concrete of very low water content, external table or plank vibration combined with superimposed load, or tamping is required.
- e. For concrete containing fiber reinforcement, external vibration is required per ASTM C 1018. It is understood that extremely low-slump fiber concrete cannot be well consolidated.

For internal vibrators, ASTM requires a minimum frequency of 7000 vibrations per min (120 Hz) and head diameter between 0.75 and 1.5 in. (20 and 40 mm). Table 5.1.5 recommends a minimum of 9000 vibrations per min (150 Hz) for internal vibrators in thin members. For vibrating tables, a minimum frequency of 3600 vibrations per min (60 Hz) is required, with higher frequencies suggested.

The intensity and time of vibration for laboratory specimens is not closely regulated. The standards merely suggest that consolidation has been achieved as soon as the specimen's surface is smooth. Entrained air may be unintentionally removed from small specimens. The concrete strength is increased about 5 percent for each percent of air removed.

Normally the consolidation of test specimens is not required to match that in construction. If it is desired to match

field concrete in the laboratory, suitable consolidation procedures must be followed. Some prefer core strengths or the strength of cubes cut from the concrete obtained from the structure as a means for estimating the strength of concrete in the structure.

16.2—Density tests

Tests for density of freshly mixed concrete (ASTM C 138) are widely used to determine the mass of the concrete per unit volume, which is used to compute the cement and air content or as a method of controlling the density of hardened lightweight concrete. The density of fresh concrete is closely related to the total air content and hence to the degree of consolidation.

ASTM C 138 requires consolidation in accordance with Section 16.1. For measures less than 0.4 ft.³ (.01 m³), rodding is required. For slumps in excess of 3 in. (75 mm), the rodding procedure should produce essentially complete consolidation, but for lower slumps the degree of consolidation may be less than in a structure where the concrete is compacted by vibration.

16.3—Air content tests

ASTM C 231 provides for consolidation by rodding for slumps greater than 3 in. (75 mm) and by rodding or vibration when slumps are 3 in. (75 mm) or less. ASTM C 173 provides for consolidation only by hand rodding.

It would appear more reasonable to follow the consolidation procedures recommended in [Section 16.1](#). Internal vibrators should be satisfactory when the slump is greater than about 1/2 in. (13 mm). Although no specific test data are available, it would appear that the pressure method, ASTM C 231, will not work properly on very harsh or low-slump mixtures. With such mixtures, the application of pressure to the surface of the concrete may not result in the expected compression of the air in the void system. The volumetric method, ASTM C 173, is not subject to this limitation and should produce accurate results on even extremely dry concrete.

ASTM C 1170 gives a method of determining the density of stiff to extremely dry concrete mixtures using a vibrating table with or without a 50 lb (22.7 kg) surcharge to consolidate the sample. The CRD C 160 method uses a 27.5 lb (12.5 kg) surcharge. These methods can be adapted to use a standard pressure air meter to determine the air content of the concrete.

16.4—Consolidating very stiff concrete in laboratory specimens

Cylinders consolidated under surcharge using ASTM C 1176 have also been used to determine the density of stiff to extremely dry mixtures. This method uses a 20 lb (9.1 kg) surcharge. Other non-standard methods have been used to consolidate cylinders by tamping equipment or vibrating compaction hammers.

It is important that the density of the laboratory concrete be close to the density of the concrete in the structure being represented. This may require a modification of the consolidation effort. During the early stages of a project it may be

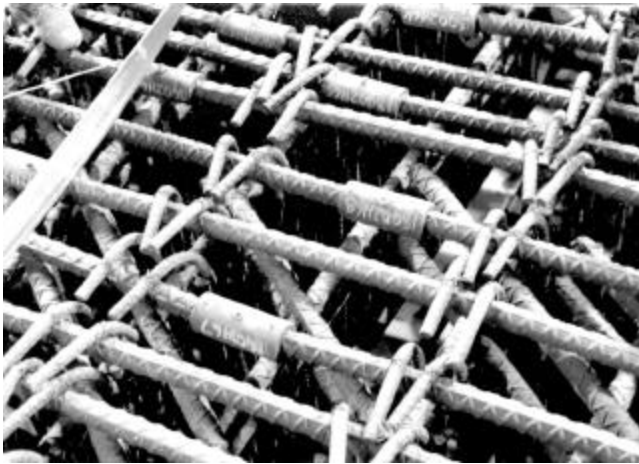


Fig. 17.1.1—Congestion due to reinforcing details

desirable to compare cylinder densities to core densities to determine the correct amount of consolidation to use.

CHAPTER 17—CONSOLIDATION IN CONGESTED AREAS*

Congested areas are areas where the lateral movement of freshly placed concrete is unduly restricted or hindered. To achieve structurally sound and esthetically pleasing concrete, special consideration must be given to select techniques that will allow proper consolidation in congested areas. Some common problems and remedial measures are described here.

17.1—Common placing problems

17.1.1 Congestion of reinforcement—Reinforcing steel congestion occurs in a variety of ways; for example, structural and seismic design requires multiple ties at the top and bottom of columns. Where design requirements override consolidation considerations, the horizontal tie spacing is often reduced so that the largest aggregate in the mixture is restricted from moving horizontally to the form face. Reinforcing steel congestion also occurs in areas where there is additional reinforcement around formed openings, particularly in thin wall sections, or columns intersecting with other elements (see Fig. 17.1.1).

17.1.2 Electrical conduit, pipe sleeves and other embedded items—Electrical designers often specify a multiple of 1 to 6-in. (25 to 150-mm) diameter conduits in localized areas for powerfeeds and cable trays. Pipe sleeves and complex structural embedments also can create barriers that affect concrete placement and consolidation (see Fig. 17.1.2).

17.1.3 Boxouts—Formed boxouts within walls and slabs can create congested zones because the concrete flow is restricted under the boxouts and between adjacent formed openings. This situation can be alleviated by adding construction joints or by adding access openings within the boxouts (see Fig. 17.1.3).



Fig. 17.1.2—Congestion due to a pipe passing through a concrete floor



Fig. 17.1.3—Large blackout within a wall with pipes through the formed blackout to permit access for concrete placement and vibration

17.2—Consolidation techniques

Consolidation in congested areas can be enhanced by special attention to construction practices in three specific areas:

1. Placing and consolidation techniques;
2. Use of admixtures;
3. Use of modified mixtures.

*See "Guide to Consolidation of Concrete in Congested Areas," ACI 309.3R.

17.2.1 Placing and consolidation techniques—The first principle of good consolidation in congested areas is to place the concrete as close to its final location as possible before consolidation. In crane and bucket applications, the use of hoppers and trunks should be considered. When using concrete pumps, wire-reinforced rubber hose attached to the boom pipe is an excellent method of getting concrete close to its final location. In extreme cases, the use of lie-flat hose is recommended. The hose will conform to the varying clearances through the reinforcement. The hose can be cut off to facilitate removal as the placement rises in the form.

In congested wall sections, the provision of placing ports in one side of the wall form insures good consolidation. The ports are located on grids patterned to address the congested areas and need to be about 2 ft. (0.6 m) square. As the concrete reaches the first set of ports, the ports are closed off and vibrators raised to the next row of ports. Additional visual access may be provided by using a transparent plastic plate as a form face in congested areas. This allows the placement crew to take additional steps to remedy problems if necessary in areas of congestion.

To achieve proper concrete consolidation in congested areas by internal vibration, obstruction-free vertical runs of 4 by 6-in. (100 by 150-mm) minimum cross section are needed to permit vibrator insertion. The horizontal spacing of these vertical runs should not exceed 24 in. (610 mm) or $1\frac{1}{2}$ times the radius of action indicated in [Table 5.1.5](#). Also, these openings should not be more than 12 in. (300 mm) or $\frac{3}{4}$ times the radius of action from the form. If such runs cannot be provided without compromising structural integrity, the engineer should specify construction details and procedures to achieve proper consolidation.

17.2.2 Use of chemical admixtures—Proper consolidation in congested areas can generally be improved by increasing the flowability of the mixture by the judicious use of concrete admixtures. They provide high-slump concrete without altering the proportioned water-cementitious material ratio. Additional information on the use of admixtures to achieve flowing concrete can be found in the report of ACI Committee 212.3R.

It must be understood that the use of chemical admixtures does not replace the requirement for good consolidation by vibration as outlined in [Chapter 7](#).

17.2.3 Use of modified mixtures—In situations where it cannot be guaranteed that the proportioned mixture will be able to flow to the form face due to congestion, the use of modified mixtures is recommended. The modified mixture containing aggregate of a reduced nominal maximum size can be used to obtain highly plastic or flowing concrete that falls into [Groups 1 and 2](#) of [Table 5.1.5](#) for vibrator selection. The modified mixture should generally be proportioned to have a strength equal to or greater than the original mixture.

17.2.4 Conclusion—The previously discussed techniques provide the designer, contractor, and supplier with methods to improve consolidation while maintaining quality. The need for quality flowable concrete is especially required in situations where extreme congestion exists and is unavoidable.

CHAPTER 18—INFORMATION SOURCES

18.1—Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed with their serial designations.

American Concrete Institute

- 116R Cement and Concrete Terminology, SP-19
- 207.1R Mass Concrete for Dams and Other Massive Structure
- 207.5R Roller Compacted Concrete
- 211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
- 211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete
- 211.3 Standard Practice for Selecting Proportions for No-Slump Concrete
- 213.1R Chemical Admixtures for Concrete
- 226.1R Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
- 226.3R Use of Fly Ash in Concrete
- 301 Specifications for Structural Concrete for Buildings
- 302.1R Guide for Concrete Floor and Slab Construction
- 303R Guide to Cast-in-Place Architectural Concrete Practice
- 304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
- 304.3R Heavyweight Concrete: Measuring, Mixing, Transporting, and Placing
- 309R Standard Practice for Consolidation of Concrete
- 309.1R Behavior of Fresh Concrete During Vibration
- 309.2R Identification and Control of Consolidation-Related Surface Defects in Formed Concrete
- 309.3R Guide for Consolidation of Concrete in Congested Areas
- 318 Building Code Requirements for Reinforced Concrete
- 347 Recommended Practice for Concrete Formwork
- 544.1R State-of-the-Art Report on Fiber Reinforced Concrete
- SP-2 ACI Manual of Concrete Inspection

ASTM

- C 31 Standard Method of Making and Curing Concrete Test Specimens in the Field
- C 138 Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
- C 143 Standard Test Method for Slump of Portland Cement Concrete
- C 173 Standard Test Method for Air Content of Freshly Mixed Concrete by Volumetric Method
- C 192 Standard Method of Making and Curing Concrete Test Specimens in the Laboratory
- C 231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
- C 637 Standard Specification for Aggregates for Radiation-Shielding Concrete
- C 638 Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete

- C 1018 Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
- C 1170 Standard Test Methods for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
- C 1176 Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table

U.S. Army Corps of Engineers

- CRD C 160 Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table
U.S. Bureau of Reclamation Concrete Manual

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428

18.2—Cited references

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21. Walz, Kurt, *Vibrated Concrete (Rüttelbeton)*, 3rd Edition, Wilhelm Ernst und Sohn, Berlin, 1960.
22. Wilde, Robert L., *Be Your Own Vibration Expert*, Koehring, Dart Division, Denver, 1970.

APPENDIX—FUNDAMENTALS OF VIBRATION

A.1—Principles of simple harmonic motion

The movement of an internal rotary concrete vibrator is essentially harmonic motion, characterized by a sinusoidal wave form, as shown in Fig. A.1. (Actually, harmonics are often superimposed, but it has been found that the assumption of simple harmonic motion is reasonably consistent with experimental data.) This figure shows the path of any point on the head of an operating vibrator and the relationship between frequency, amplitude, and acceleration.

A.2—Action of a rotary vibrator

Rotating the eccentric inside the vibrator head or casing causes the head to revolve in an orbit; that is, any point on the casing follows a circular path whose radius is the amplitude of the vibrator. Fig. A.2 shows the action of a rotary vibrator and gives the significant parameters, for example, mass, eccentric moment, frequency, centrifugal force, and computed average amplitude.

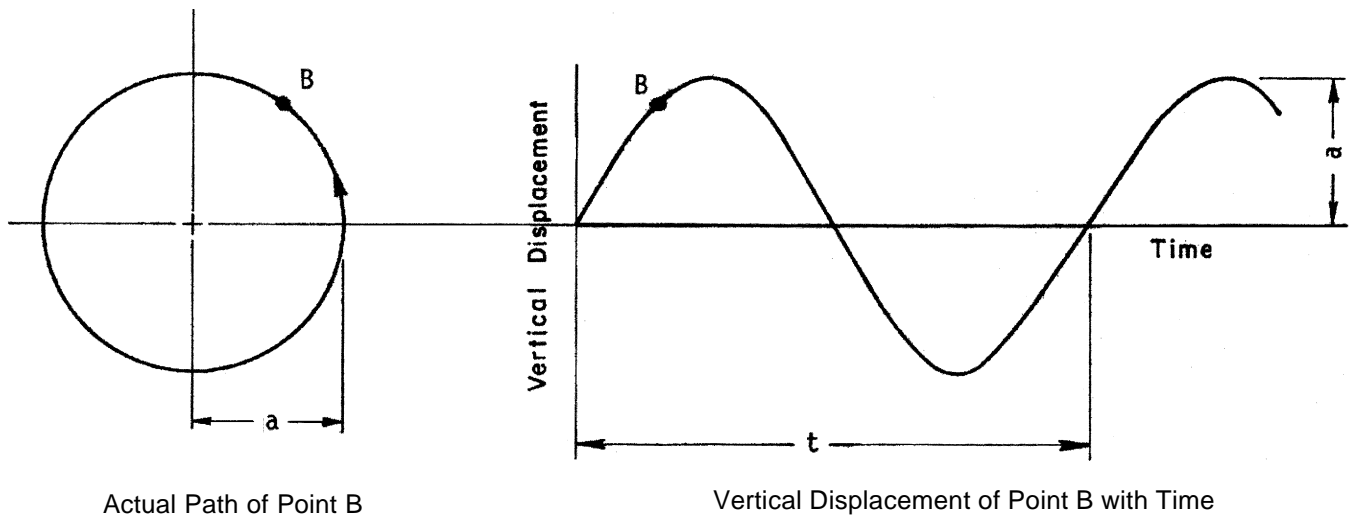
The centrifugal force computed in this manner is not strictly correct, since it is for the hypothetical case where the vibrator shell has zero amplitude while the rotor (eccentric) turns in its bearings. In spite of these limitations, however, the values thus obtained are useful as a rough indicator of the relative effectiveness of different vibrators.

A.3—Vibratory motion in the concrete

When immersed in concrete, the orbiting head (now under load) has a somewhat lesser amplitude than when operating in air. The concrete is subjected to vibratory impulses which produce wave motion emanating at right angles to the head. These pressure waves are mainly responsible for the consolidation.

The waves decay rapidly with distance from the source because of the expanding area of the wave front and the absorption of energy (damping) by the concrete. This decay (reduction in amplitude) causes a reduction in the acceleration (intensity of vibration). Where the acceleration in the concrete is less than about 1 g for plastic mixes, or about 3 gs for stiff mixes, the vibration is no longer effective. A considerable amplitude at the vibrator is required to attain a satisfactory radius of action.

The response of fresh concrete to vibration is largely a function of its rheological (flow) properties. Much more research is needed on this subject.

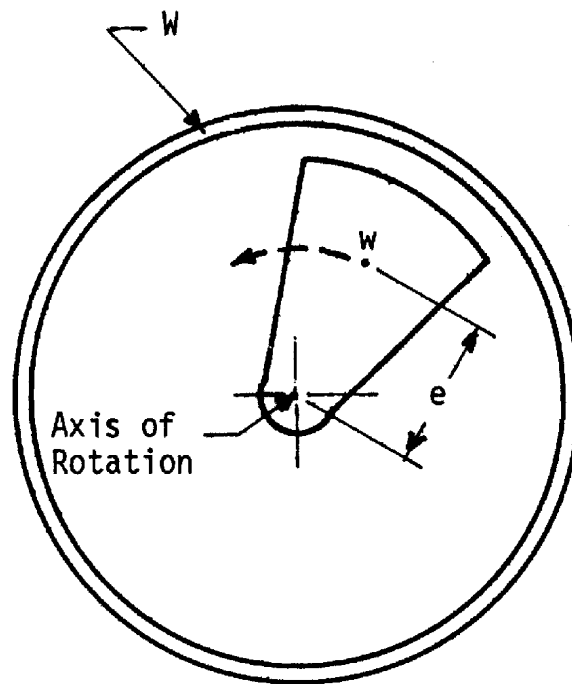


- B = random point on vibrator spud
 t = time for one complete revolution or vibration cycle, sec
 n = $1/t$ = frequency, vibration cycles or vibrations per sec (Hz)
 a = amplitude (deviation from point of rest), * in. (mm)
 $A = 4\pi^2 n^2 a$ = acceleration, in. per sec² (mm/sec²)

$$\text{Acceleration, } g\text{'s,} = \frac{4\pi^2 n^2 a}{g}, \text{ where } g \text{ is } 386 \text{ in.}$$

* It should be noted that amplitude as used here (and elsewhere in this report) is peak amplitude, which is half the peak-to-peak amplitude or displacement used by some in describing vibrations.

Fig. A.1—Principles of simple harmonic motion applied to rotary vibrator



- W = weight of shell and other nonmoving parts, lb (kg)
 w = weight of eccentric, lb (kg)
 $W+w$ = total weight of vibrator
 e = eccentricity, i.e., distance from center of gravity of eccentric to its center of rotation, in. (mm)
 we = eccentric moment, in.-lb (mm-kg)
 n = frequency, cycles per sec (Hz)
 $F = \frac{w}{g} 4\pi^2 n^2 e$ = centrifugal force, lb (kN)
 $a' = w \frac{e}{W+w}$ = computed average amplitude, in. (mm)

Fig. A.2—Action of a rotary vibrator