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Report on Behavior of Fresh Concrete During Vibration

Reported by ACI Committee 309

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

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

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Forssblad (1965a) reported on measurements of the radius of action of internal vibrators operating at different frequencies and amplitudes, and with different vibration times and mixture consistencies. The radius of action was determined from photographs of the concrete surface.

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

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

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

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

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

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

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

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

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

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

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

An International Symposium on Concrete Consolidation was sponsored by ACI Committee 309 and presented in 1986 in San Francisco. Papers relating to the behavior of fresh concrete during vibration included the following:

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

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

In the 1980s, the methods used to place and consolidate many concretes began to change away from the traditional internal or form vibrators. Roller-compacted concrete (RCC) began to be used as a method for rapidly placing no-slump mass concrete with compaction by smooth-drum, vibrating rollers common to embankment construction. The increase in consolidation production per unit equipment went from about 300 yd^3 (230 m^3) per shift to 3000 yd^3 (2295 m^3) per shift in mass applications (Dolen 2002). RCC construction diverged in the 1980s into two different methodologies: a concrete approach and a soils approach. The concrete approach followed a more traditional mass concrete technology; the consistency of the concrete was measured by the modified Vebe time, which replaced the slump test. A Vebe consistency of about 20 seconds, according to ASTM C1170, became common for mass dam applications where the RCC was placed in about 1 ft (300 mm) thick lifts. RCC pavements and embankment dam overtopping applications took the soils approach by using the modified Proctor test to place the concrete at optimum moisture content suitable for maximum dry density in about 6 to 9 in. (150 to 225 mm) thick lifts (Ragan 1988).

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

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

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

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a = acceleration, ft/s^2 (m/s^2)
c = wave velocity, ft/s (m/s)
c_1 = constant, depending on stiffness and damping in the concrete
E = dynamic modulus of elasticity, lb/ft^2 (MPa)
F = force, lbf (N)
f = frequency, Hz
g = acceleration due to gravity, in./s^2 (mm/s^2)
h = depth below surface, ft (m)
m = concrete mass, lb/(32.2 ft/s^2) (kg/[9.81 m/s^2])
m_e = weight of eccentric, lb (kg)
m_v = vibrator weight minus the eccentric weight, lb (kg)
m_b = weight of displaced concrete, lb (kg)
r = eccentricity of the eccentric weight, in (mm)
s = amplitude, in. (mm)
s_x = amplitude at distance x from a reference point, in. (mm)
t = time, s
v = maximum particle velocity, ft/s (m/s)
γ = density, lb/ft^3 (kg/m^3)
$\dot{\gamma}$ = linear relationship between shear stress and shear rate of concrete
η_{pl} = plastic viscosity of concrete
σ = shear stress of concrete
σ_B = Bingham yield stress of concrete
ω = angular velocity, radian/s
Ω = coefficient of damping

2.2—Definitions

consistency—the degree to which a freshly mixed concrete, mortar, grout, or cement paste resists deformation. (See also: **consistency, normal**; **consistency, plastic**; and **consistency, wettest stable**.)

consistency, normal—(1) the consistency exhibited when a mixture is considered acceptable for the purpose at hand; or (2) the consistency of cement paste satisfying appropriate limits defined in a standard test method (for example, ASTM C187).

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

consistency, wettest stable—the condition of maximum water content at which cement grout and mortar will adhere to a vertical surface without sloughing.

consistency factor—a measure of grout fluidity, roughly analogous to viscosity, that describes the ease with which grout may be pumped into pores or fissures; usually a laboratory measurement in which consistency is reported in degrees of rotation of a torque viscometer in a specimen of grout.

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

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

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

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

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

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

workability (**placeability**)—that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition.

CHAPTER 3—INFLUENCE OF RHEOLOGY ON CONSOLIDATION OF FRESH CONCRETE

3.1—Rheology of fresh concrete

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

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

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

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

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

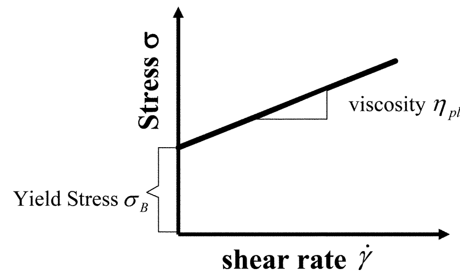


Fig. 3.1—Bingham model.

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

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

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

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

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

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

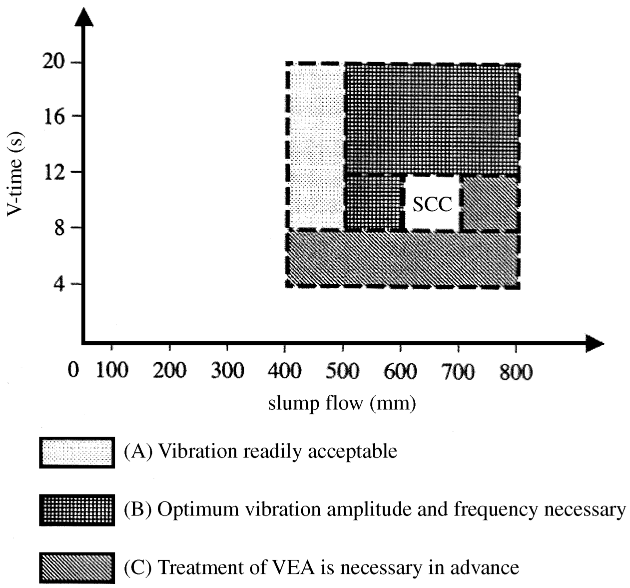


Fig. 3.2—Vibration susceptibility of high-fluidity concrete (1 in. = 25.4 mm).

is achieved by placing the concrete from a hand scoop into the base container of the standard apparatus, without compaction, and then striking off the surface of the full container. The other measurement determines the density of mechanically vibrated concrete sampled from the same batch; the concrete was loosely placed and compacted in three layers in the base container with a 1 in. (25 mm) diameter internal vibrator. These two readings plus the values obtained from the standard compacting factor test give an indication of the relative ease of changing a mixture from a loose to a compacted state. In addition, the difference between the actual compacted state and the theoretical maximum compaction, calculated from the specific gravity of the constituents, gives a relative measure of the void content of the concrete and, hence, an indication of its durability, permeability, and relative strength of the hardened concrete.

Little research has been conducted to examine the relationship between rheological parameters as defined by Bingham and consolidation of concrete. The main question is how concrete rheological properties change with vibration. One of the reasons for the lack of research is the difficulty in measuring the plastic viscosity and yield stress while the concrete is being vibrated, as only one rheometer, the BTRHEOM, has that capability. Banfill et al. (1999) and Kitaoji et al. (1998) did the most extensive research on the topic, while Chong (1995) was able to perform some measurements. Other studies (Chia et al. 2005; Safawi et al. 2005) limited research to the characterization of segregation and rheological parameters before vibration. Banfill et al. (1999) observed that the application of vibration results in the reduction to zero of the yield stress while the plastic viscosity is not affected. This observation was quantified by Chong (1995), who stated that the yield stress of a concrete under vibration is about half the yield stress of nonvibrated concrete. Kitaoji et al. (1998) observed that plastic viscosity is responsible for the attenuation of the radius of influence of a vibrator, while the yield stress has no influence. Safawi et al. (2005) characterized a concrete using flow time through a funnel and the slump flow. He then established a relationship between these parameters and the segregation measured for coarse aggregates under vibration. He found that the plastic viscosity measured indirectly by the flow time through a funnel had a major impact on segregation: high viscosity leads to low or no segregation, while low viscosity leads to high segregation. Figure 3.2 shows the vibration susceptibility of concrete depending on the flow time (V-time) and slump flow.

3.2—Rheology in practice

To optimize consolidation of concrete, various methods are available: rodding, vibration, or using a well designed SCC. The properties that need to be optimized are yield stress and plastic viscosity as defined by Bingham. The composition of the concrete has a large impact on the yield stress and plastic viscosity. The operator should be aware of the influence of chemical admixtures, supplementary cementitious materials, shape and gradation of the aggregates, and potential incompatibility between materials. A detailed discussion of the influence of each constituent can be found in ACI 238.1R.

3.2.1 *Mixture proportioning*—Concrete mixtures are proportioned to provide the workability needed during construction and to assure that the hardened concrete will have the required properties. Mixture proportioning is described in detail in ACI 211.1, 211.2, and 211.3R.

3.3—Conclusions

Although the required compacting effort cannot presently be expressed in terms of the rheological properties of concrete, knowledge of these properties is beneficial in selecting concrete mixtures that can be efficiently compacted in the forms. Good progress toward better understanding of the rheology of fresh concrete has been achieved in recent years, as evidenced by the reported research. Further study is yet required to provide the construction industry with a relatively simple standard test method for both laboratory and field.

CHAPTER 4—MECHANISMS OF CONCRETE VIBRATION

4.1—Introduction

Vibration has been used for almost all types of concrete construction, yet knowledge of the theory and mechanism of concrete vibration is surprisingly limited. The following analysis of vibration mechanisms deals with the general rules governing concrete vibration and the different types of vibratory methods (Popovics 1973).

4.2—Vibratory motion

Concrete vibrators generally use a rotating eccentric weight. Such vibrators generate harmonic motion, characterized by a sinusoidal wave form (Fig. 4.1).

Sinusoidal oscillation is defined by Eq. (4-1)

$$x = s\sin\omega t = s\sin 2\pi ft \tag{4-1}$$

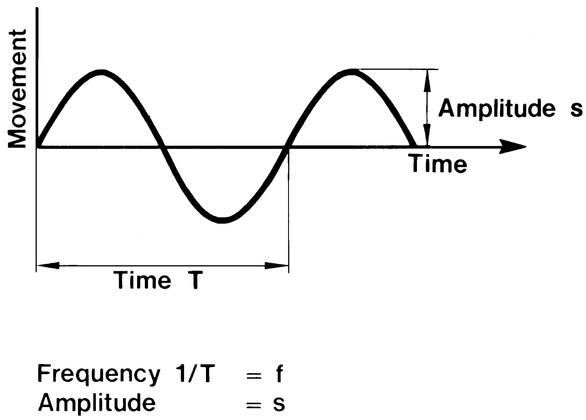


Fig. 4.1—Sinusoidal vibratory motion.

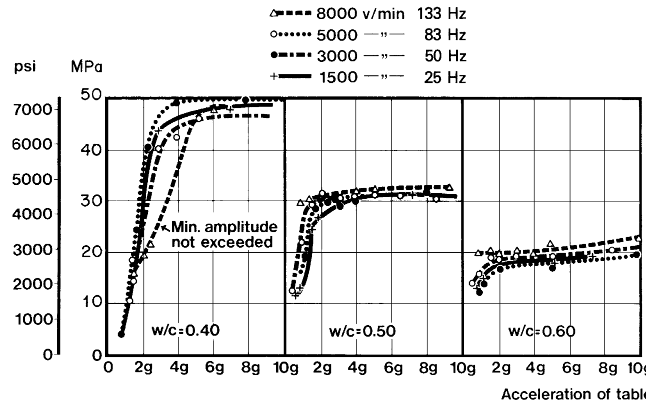


Fig. 4.2—Correlation between compressive strength of hardened concrete and acceleration during vibrating tests on vibrating table.

where

s = amplitude, in. (mm);
ω = angular velocity, radian/s;
f = frequency, Hz; and
t = time, s.

From this equation, the relationships shown in Eq. (4-2) and (4-3) are obtained

$$\dot{x} = 2\pi fs\cos 2\pi ft = v\cos\pi ft \tag{4-2}$$

where $v = 2\pi fs$ = maximum particle velocity during the oscillatory motion, in./s (mm/s).

$$\ddot{x} = 4\pi^2 f^2 s\sin 2\pi ft = a\sin 2\pi ft \tag{4-3}$$

where $a = 4\pi^2 f^2 s$ = maximum acceleration during the oscillatory motion, in./s^2 (mm/s^2).

4.3—Parameters of concrete vibration

Vibratory consolidation of granular materials is achieved by setting the particles into motion, thus eliminating the internal friction. L'Hermite and Tournon (1948) showed that the internal friction in fresh concrete during vibration is 0.15 psi (0.001 MPa) compared with about 3 psi (0.02 MPa) at rest. Thus, internal friction during vibration is reduced to about 5% of the value at rest.

Figure 4.2 indicates that consolidation of fresh concrete starts at an acceleration of about 0.5 g (4.9 m/s^2). Concrete compression strength is used as an indicator of how thoroughly the concrete is compacted, because the lack of voids increases the compression strength values. The compaction effect then increases linearly to an acceleration between 1 and 4 g (9.8 and 39.2 m/s^2), depending on the consistency of the concrete. A further increase in acceleration does not increase the compaction effect. The left diagram in Fig. 4.2 shows that acceleration alone is not sufficient; a minimum amplitude is also required. A minimum value for the amplitude of 0.0015 in. (0.04 mm) was proposed by Kolek (1963).

The correlation between acceleration and the effect of the vibration for normal concrete mixtures indicates that equivalent compaction results can be obtained within a relatively large frequency range, as shown in Fig. 4.2. Table 4.1 shows that the strength of the hardened concrete is mainly independent of frequency and amplitude as long as the minimum acceleration is exceeded.

Forssblad (1965b) showed efficient vibratory compaction of moist soils when dynamic pressure forces were 7 to 15 psi (0.05 to 0.1 MPa). The dynamic pressures are required to overcome the capillary forces between the particles of moist granular material.

During vibratory consolidation, energy transmitted to the concrete is another important parameter. The energy can be calculated by Eq. (4-4), as postulated by Kirkham and White (1962)

$$W = c_1 ms^2 f^3 t \tag{4-4}$$

where

W = energy, ft-lb (J);
c_1 = constant, depending on stiffness and damping in the concrete;
m = concrete mass, lb/(32.2 ft/s^2) (kg/[9.81 m/s^2]);
s = amplitude, ft (m);
f = frequency, Hz; and
t = time, s.

In summary, requirements for the consolidation of fresh concrete are as follows:

1. Minimum acceleration for concrete of normal consistencies;
2. Minimum dynamic pressure for very stiff concrete consistencies;
3. Minimum vibratory amplitude for any given mixture; and
4. Minimum vibratory energy for all mixtures.

4.3.1 *Wave transmission through fresh concrete*—The transmission of a sinusoidal compression wave through an elastic medium is expressed by Eq. (4-5)

$$s_x = s_o e^{-\Omega x/2} \tag{4-5}$$

where

Table 4.1—Compressive strength and density of concrete specimens vibrated with internal vibrators at various frequencies and amplitudes

	Specimen												Mean	Coefficient of variation, %
	1	2	3	4	5	6	7	8	9	10	11	12		
At 7500 cpm and 0.063 in. (1.6 mm) amplitude														
Compressive strength, psi (MPa)	6020 (41.5)	6420 (44.3)	6240 (43.0)	6210 (42.8)	6090 (42.0)	6150 (42.4)	6350 (43.8)	6050 (41.7)	7060 (48.7)	6760 (46.6)	6900 (47.6)	6960 (48.0)	6440 (44.4)	±6
Density, lb/ft^3 (kg/m^3)	149 (2390)	150 (2410)	150 (2400)	150 (2400)	151 (2420)	152 (2430)	152 (2440)	151 (2420)	150 (2400)	150 (2410)	152 (2430)	150 (2410)	150 (2410)	±0.6
At 9500 cpm and 0.047 in. (1.2 mm) amplitude														
Compressive strength, psi (MPa)	6280 (43.3)	6470 (44.6)	6440 (44.4)	6560 (45.2)	6110 (42.1)	6210 (42.8)	6480 (44.7)	6500 (44.8)	6980 (48.1)	7060 (48.7)	7270 (50.1)	7250 (50.0)	6630 (45.7)	±6
Density, lb/ft^3 (kg/m^3)	149 (2380)	149 (2390)	149 (2390)	149 (2390)	150 (2410)	150 (2410)	152 (2430)	151 (2420)	151 (2420)	153 (2450)	154 (2460)	154 (2460)	151 (2420)	±12
At 12,000 cpm and 0.059 in. (1.5 mm) amplitude														
Compressive strength, psi (MPa)	6290 (43.4)	6870 (47.4)	6610 (45.6)	6410 (44.2)	6320 (43.6)	6440 (44.4)	6510 (44.9)	6540 (45.1)	7140 (49.2)	7280 (50.2)	7380 (50.9)	7320 (50.5)	6760 (46.6)	±6
Density, lb/ft^3 (kg/m^3)	149 (2390)	150 (2410)	151 (2420)	150 (2410)	150 (2400)	150 (2410)	152 (2430)	151 (2420)	152 (2440)	153 (2450)	153 (2450)	154 (2460)	151 (2420)	±0.9
At 17,000 cpm and 0.03 in. (0.7 mm) amplitude														
Compressive strength, psi (MPa)	5820 (40.1)	5820 (40.1)	6030 (41.6)	6020 (41.5)	5790 (29.9)	6400 (44.1)	6920 (47.7)	6130 (42.3)	7370 (50.8)	7340 (50.6)	7590 (52.3)	7300 (50.3)	6540 (45.1)	±1.1
Density, lb/ft^3 (kg/m^3)	148 (2370)	148 (2370)	150 (2410)	148 (2370)	148 (2370)	150 (2410)	152 (2440)	151 (2420)	149 (2380)	150 (2410)	152 (2440)	151 (2420)	150 (2400)	±1.1

s_x = amplitude at distance x from a reference point where the amplitude is s_o, in. (mm); and
Ω = coefficient of damping.

The maximum pressure p generated during the transmission of a sinusoidal compression wave is calculated using Eq. (4-6)

$$p = vc\gamma \tag{4-6}$$

where
v = maximum particle velocity, ft/s (m/s);
c = wave velocity, ft/s (m/s); and
γ = density, lb/ft^3 (kg/m^3).

Thus, the maximum pressure is directly proportional to the maximum particle velocity which, in turn, is a product of frequency and amplitude. According to general theories for wave transmission through an elastic medium, the relationship given in Eq. (4-7) exists

$$c = \lambda f = \frac{E}{\gamma} \tag{4-7}$$

where
γ = wave length, ft (m);
f = frequency, Hz; and
E = dynamic modulus of elasticity, lb/ft^2 (MPa).

Researchers have reported different values for the wave velocity in fresh concrete. During the first stage of vibration, the velocity is about 150 ft/s (45 m/s) (Halken 1977). Wave velocities between 200 and 800 ft/s (60 and 250 m/s) have been reported for vibration periods of 1 to 2 minutes. An average value of 500 ft/s (150 m/s) and a frequency of 200 Hz correspond to a wave length of 2.5 ft (0.75 m). Laboratory tests conducted by Halken (1977) established a value of 500 psi (3 MPa) for the dynamic modulus of elasticity of fresh concrete.

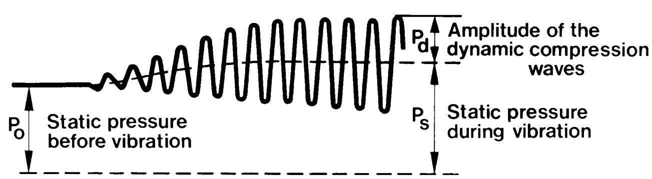


Fig. 4.3—Transmission through vibration from state of rest to fluid state.

4.3.2 *Vibration process*—It is important to analyze the different stages of concrete consolidation. L'Hermite and Tournon (1948) showed great differences in properties of concrete at rest and during vibration.

Transmission from the state of rest to the fluid vibrating state was shown schematically by Bergstrom and Linderholms (1949) (Fig. 4.3). Kolek (1963) suggested a further division of the vibration process: the first stage comprises the usually rapid subsidence of the uncompacted mixture, which is followed by the deaeration stage (removal of entrapped air). During the latter stage, segregation of the fresh concrete can take place, especially with fluid mixtures and prolonged vibration periods. Popovics and Lombardi (1985) recommended a device for recording the consolidation of fresh concrete by vibration.

Alexander (1977) investigated the vibration process by measuring the mechanical impedance (Fig. 4.4). At low levels of vibratory motion, the concrete was characterized by high damping and stiffness. No resonant frequency was determined. At high intensities of vibratory motion, the impedance dropped by a factor of 5 to 10, which is lower than the value of about 20 reported by L'Hermite and Tournon (1948). After transformation, the vibratory motion was controlled by the mass forces with little or no effect from stiffness or damping, which indicated that the concrete during vibration behaves like a fluid. Because inertia is the primary hindrance to motion, Newton's second law of motion given in Eq. (4-8) can be applied

$$F = ma \tag{4-8}$$

where

F = force, lbf (N);
m = units of mass; and
a = acceleration, ft/s^2 (m/s^2).

This further indicates that acceleration is a major factor in the consolidation of concrete by vibration.

Figure 4.5 shows three types of behavior of fresh concrete that take place within a few seconds of each other. First, if the force level being used to vibrate the concrete is below that required to get the concrete to flow, the impedance will be according to Curve 1. The impedance can be described by a simple model made up of one stiffness element K, one mass element M, and one damping element C. When connected in the correct fashion, the impedance is determined by Eq. (4-9)

$$z = \sqrt{C^2 + (\omega M - k/\omega)^2} \tag{4-9}$$

If the excitation force is suddenly increased to a higher level, the mechanical properties change, and the impedance momentarily falls until the material changes from a solid to a liquid form. This decrease in impedance is shown by Curve 2. As long as the higher force level is maintained, the impedance will track up and down a mass line indicated by Curve 3 as the frequency is varied. It is understood that as the impedance is following a mass line, the system being vibrated is a pure mass without damping and stiffness. The three types of straight lines shown—horizontal, slanting down to right, and slanting up to right—are preprinted on mechanical impedance paper to allow one to easily visualize the mechanical motion taking place. If the impedance tracks down one of the lines slanting to the right, it will indicate that the system being vibrated is pure stiffness. If the impedance tracks across one of the horizontal lines, then the system being vibrated is a pure damper. All combinations are possible, and most physical systems consist of all three mechanical elements: masses, springs, and dampers.

Because concrete mixtures of normal consistencies behave like a fluid during vibration, hydrodynamic theories are best suited to calculate the processes and mechanisms of concrete vibration.

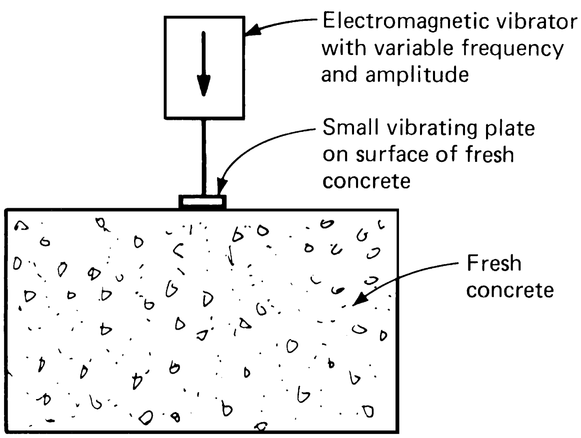


Fig. 4.4—Impedance test.

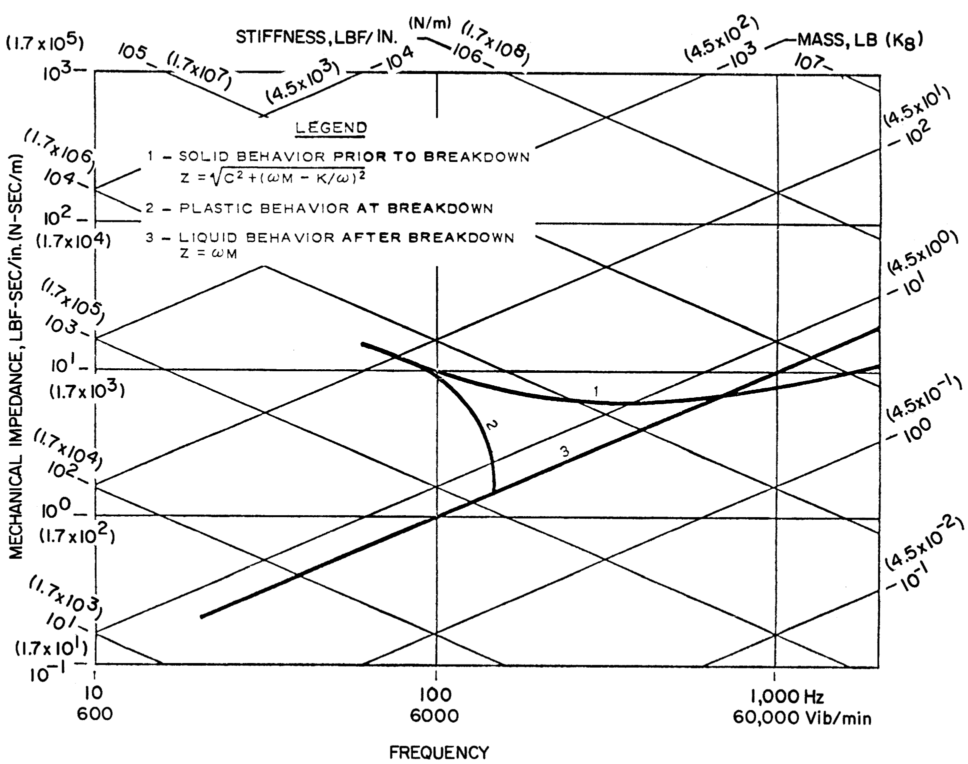


Fig. 4.5—Three types of behavior of fresh concrete.

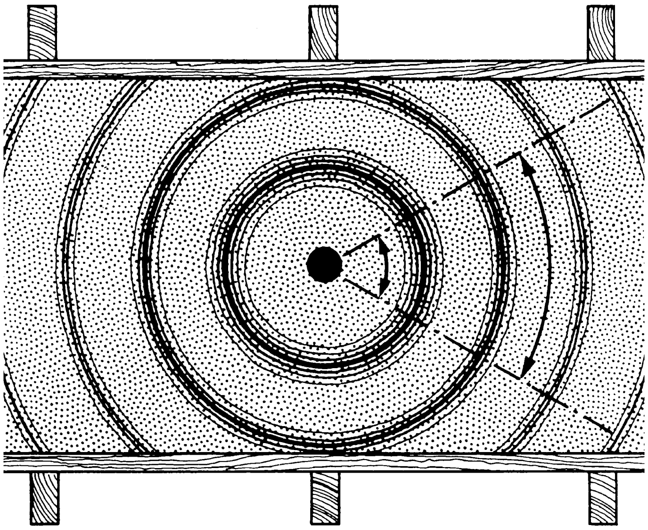


Fig. 4.6—Principle of internal vibration.

The fluid mixture has no resonant frequency. Alexander's (1977) study showed the same results for unconsolidated concrete.

Rheological models containing spring-supported masses cannot readily simulate the behavior of a fresh flowing to plastic concrete. Theories presuming that fresh concrete behaves like an elastic body, as suggested by Bache (1973) and Jurecka (1968), are applicable only to very stiff mixtures.

Bache (1973) suggested the application of hydrodynamic theories based on the bubble movements in the fresh concrete. Studies on the same subject were also made by Smalley and Ahmad (1973). The tendency of the bubbles to move upward depends on their buoyancy. There is also a tendency for the bubbles to move toward a vibrating surface, or even downward. For this reason, excessive vibrations of forms or form sections should be avoided.

Bache (1977) also discussed the stability of freshly compacted concrete. This stability is dependent on internal friction, cohesion, and capillary pressure. The use of crushed aggregate increases internal friction. A high capillary surface pressure can be obtained by vacuum treatment or by static or dynamic pressure created during vibration.

4.3.3 *Energy consumption*—The initial rapid subsidence of the mixture during vibration can be characterized as plastic deformation that requires a large energy consumption; for complete consolidation, the entire transmitted energy is consumed.

During the final deaeration stage of vibration, no additional energy is necessary to keep the mass in motion because the mixture behaves like a fluid without damping. In an ideal fluid, the energy consumption of the vibrator is theoretically the same as in air. A small internal friction and damping remains during the deaeration stage, thus requiring a limited energy supply.

4.4—Vibratory methods

Thus far, the discussion on the mechanisms of vibration has covered only general rules relating to the influence of vibration on the freshly mixed concrete. For the different vibratory methods, the entire vibrating system, including vibrator, fresh concrete mixture, and effect of the form, should be studied.

4.4.1 *Internal vibration*—An internal vibrator immersed in fresh concrete generates rapidly recurring circular compression waves (Fig. 4.6). The wave amplitudes rapidly decrease with increasing distance from the vibrator.

To obtain an adequate radius of action, an internal vibrator should operate at a high vibration intensity. The effects of internal vibrators on fresh concrete have been studied by Bergstrom and Linderholms (1949), Ersoy (1962), Forssblad (1965a), Taylor (1976), Goldstein (1968), and Soutsos et al. (1999).

Bergstrom and Linderholms (1949) and Forssblad (1965a) measured the radii of action of vibrators at various time intervals on the basis of photographs of the concrete surface. Relationships between frequency, amplitude, and radius of action for a 2-1/2 in. (60 mm) internal vibrator after 10 and 30 seconds of vibration are shown in Fig. 4.7. The largest radius of action occurred at an optimum frequency of about 200 Hz (12,000 vibrations/min.). An increase in amplitude resulted in an increased radius of action at all frequencies. At lower frequencies, an approximate relationship existed between the acceleration of the vibrator and its radius of action.

An optimum frequency for internal vibration was confirmed by experimental tests by Taylor (1976) and Goldstein (1968). Frequency curves presented by Ersoy (1962), however, did not indicate optimum values. In his study, Ersoy used small forms, 34 x 8 x 8 in. (850 x 200 x 200 mm), which may have influenced the test results. It is possible that reflections from the form walls and vibrations of the forms caused higher accelerations than would be the case in larger forms. Hover (2001) reported that vibrator frequency is a key to the ability to consolidate fresh concrete. When the frequency is too low, the vibrator can't properly consolidate the concrete; and when the frequency is too high, air-entrained concrete can become less resistant to damage caused by cyclic freezing.

Results of research by Taylor (1976) indicate that accelerations for internal vibrations should range from 100 to 200 g (980 to 1960 m/s^2) for concrete with maximum aggregate sizes of 1-1/4, 3/4, and 3/8 in. (38, 19, and 10 mm). For a given acceleration, an internal vibrator will have an increased radius of action at increased amplitudes.

Taylor (1976) and Ersoy (1962) measured the density of hardened concrete by nuclear density tests as a means of determining the effective radius of action of vibrators. Forssblad (1965a) investigated the influence of concrete consistency, maximum aggregate size, form dimensions, form design, and reinforcing steel on the performance of internal vibration. Tests by these authors indicate that the maximum aggregate size may be an important parameter for the effectiveness of internal vibration.

In fresh concrete, the amplitude of the vibrator head is reduced by the resistance of the concrete to the movement. According to hydrodynamic theories, the effect of a surrounding fluid on a vibrating body may be represented by

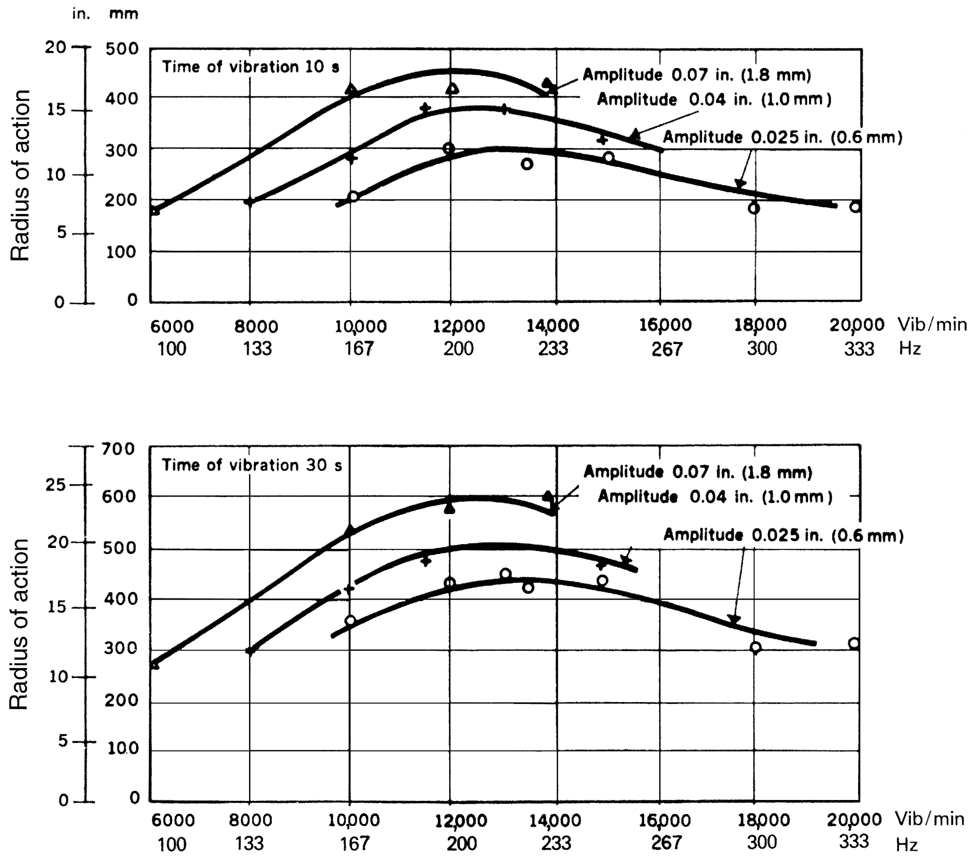


Fig. 4.7—Correlation between radius of action, frequency, and amplitude for a 2.5 in. (60 mm) internal vibrator.

the addition of a mass to the body. In the case of a vibrating cylindrical body, this mass is equal to the mass of the displaced fluid (Lamb 1945). It is then possible to calculate the acceleration a of a cylindrical internal vibrator operating in concrete by Eq. (4-10)

$$a = \frac{4\pi^2 f^2 m_e r}{m_v + m_e + m_b} \tag{4-10}$$

where

a = acceleration, in./s^2 (mm/s^2);
f = frequency, Hz;
m_e = weight of eccentric, lb (kg);
r = eccentricity of the eccentric weight, in. (mm);
m_v = vibrator weight minus the eccentric weight, lb (kg); and
m_b = weight of displaced concrete, lb (kg).

The amplitude of an internal vibrator operating in concrete is approximately 70 to 75% of its amplitude in air, which indicates good agreement between calculated and measured values (Fig. 4.8).

The centrifugal force F, which sometimes is used as a parameter of an internal vibrator, is calculated by Eq. (4-11)

$$F = 4(\pi^2 f^2) m_e r \frac{1}{g} \tag{4-11}$$

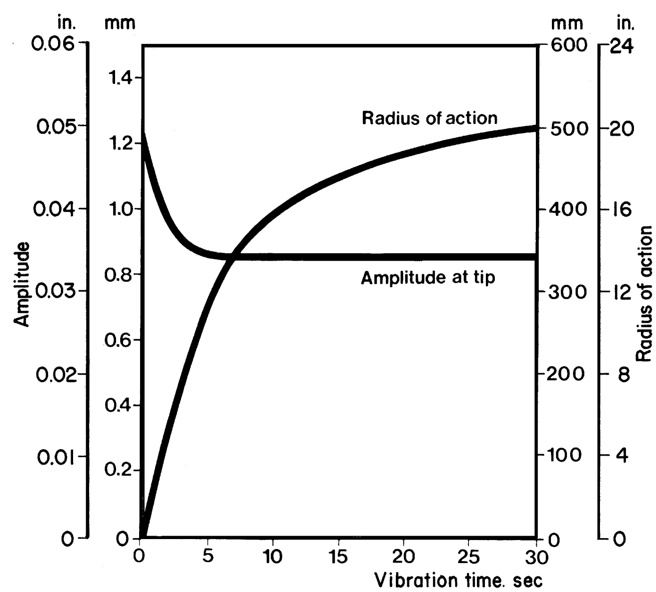


Fig. 4.8—Amplitude and radius of action of internal vibrator.

where

F = centrifugal force, lbf (N); and
g = acceleration due to gravity, in./s^2 (mm/s^2).

According to hydrodynamic principles, the weight of the displaced concrete mass is directly related to the mass of

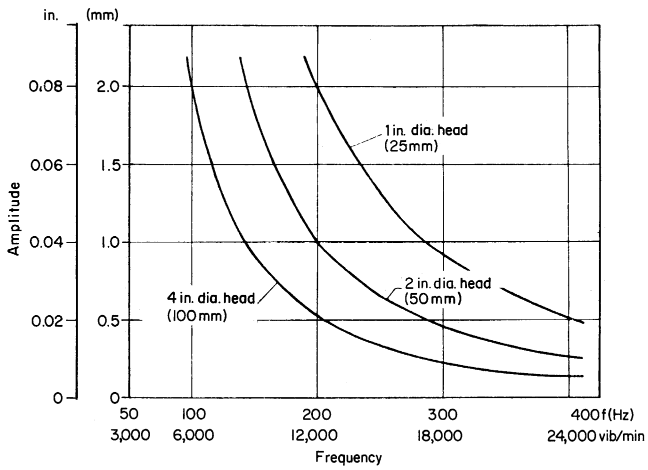


Fig. 4.9—Frequencies and amplitudes not to be exceeded to avoid cavitation.

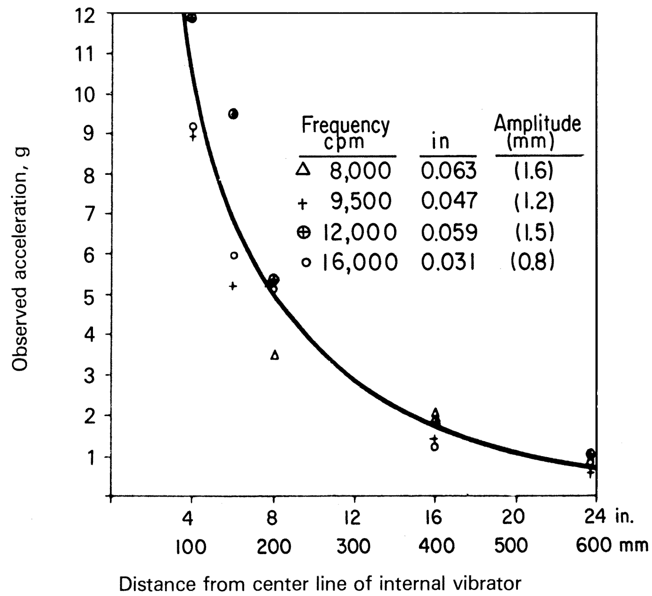


Fig. 4.10—Example of damping for measured accelerations at different distances from internal vibrator.

concrete placed in vibratory motion. As the displaced mass is proportional to the area of the vibrator head, it follows that the radius of action is directly proportional to the head diameter of the internal vibrator. This has been confirmed by tests (Forssblad 1965a).

In a homogeneous fluid, the amplitude generated around the vibrating head will be the same as the amplitude of the vibrator. Concrete, however, is not a homogeneous material. During vibration, cement paste will surround the vibrator, which may result in a reduction in energy transmission from the vibrator to the fresh concrete. This reduction should be determined empirically.

Pressure reductions are generated in the fluid mixture by the sinusoidal compression waves during half of their periods. At increasing vibration intensity, the creation of vapor and gas bubbles, representing the initial stage of cavitation, can reduce the energy transmission between the vibrator and the concrete. These bubbles are likely to act as shock absorbers and dampen the compression waves. At decreasing pressures, small bubbles merge to form large vapor pockets which can be observed close to internal vibrators that are operating at high acceleration.

Cavitation starts when the pressure amplitude P_c of the compression waves exceeds the available pressure shown in Eq. (4-12)

$$P_c \geq \underset{\text{Atmospheric pressure, MPa}}{1.0} \quad \underset{\text{Hydrostatic pressure, MPa}}{+\gamma g h} \quad \underset{\text{Vapor pressure, MPa}}{-0.03} \tag{4-12}$$

where

γ = density, lb/ft^3 (kg/m^3);

g = acceleration due to gravity (m/s^2); and

h = depth below surface, ft (m).

Curves were developed for internal vibrators of different diameters, which show combinations of frequencies and amplitudes that should not be exceeded if cavitation is to be avoided (Fig. 4.9).

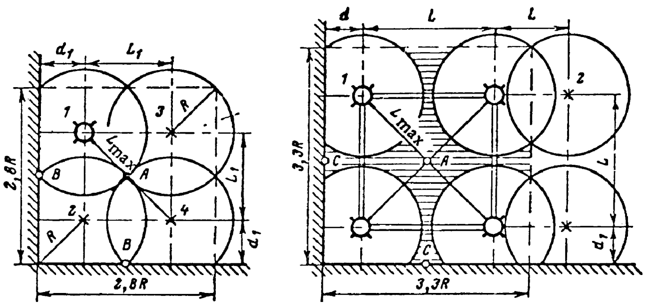
The geometrical energy distribution due to the radial generation of compression waves, as well as the damping, can be calculated by Eq. (4-13) as postulated by Dessoff (1937)

$$s_2 = s_1 \frac{R_2}{R_1} e^{-(\Omega/2)(R_2 - R_1)} \tag{4-13}$$

where s_1 and s_2 are the amplitudes at the respective distances of R_1 and R_2 from the center of the internal vibrator. Ω is the coefficient of damping. For flowing to plastic concrete, a value of Ω between 0.04 and 0.08 is normal. Damping may be dependent on the small residual internal friction in the fresh concrete, and can be assumed to be of a hysteretic character. Damping of this type is proportional to the amplitude. At constant amplitude, the energy absorption is constant for each cycle, independent of the frequency. The total energy absorption will thus increase linearly with the frequency as well as with the amplitude.

According to Dessoff's (1937) formula, the material damping coefficient of 0.04 represents approximately 15% of total damping, and the geometric energy distribution is 85% of the total decrease in amplitude with increasing distance from the vibrator. A damping coefficient of 0.08 that corresponds to 20% of the total damping means that the geometric energy distribution dominates. Even if, as indicated by L'Hermite and Tournon (1948), it is more dependent on frequency than assumed herein, the total damping remains essentially independent of the frequency (Fig. 4.10).

A study by Chen et al. (1976) investigated a vibrating rod in a viscous fluid. When the rod vibrates in a large container filled with a low-viscosity fluid such as water, the vibrating fluid mass is the same as the volume displaced by the rod, in accordance with Lamb's theory. At increasing viscosity, the vibrating fluid mass and the damping are both increased by a factor proportional to the viscosity.



(a) Single vibrators (b) Frame-mounted vibrators

Fig. 4.11—Disposition of internal vibrators.

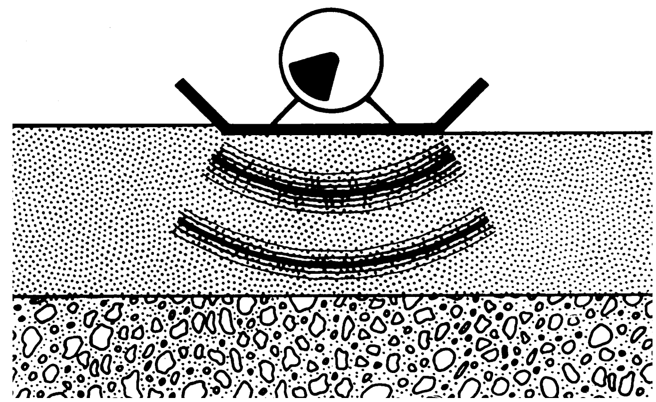


Fig. 4.12—Principle of surface vibration.

During the initial phase of consolidation by vibration, a large energy absorption due to the plastic deformation and consolidation of the noncompacted mass takes place. During the second deaeration stage, the energy absorption decreases rapidly. Transmission of vibrations to an ideal fluid does not imply any increase of the power input to the vibrator compared with the energy consumption in air. The material damping indicates, on the other hand, the existence of some energy absorption also during the second stage of vibration. The radius of action of an internal vibrator is substantially less in reinforced concrete than in nonreinforced concrete. A reduction of 50% is not uncommon (Forssblad 1965a).

Limiting factors for the transmission of vibrations through fresh concrete have been mentioned. Working in a positive way, however, is the reflection of the compression waves from the form walls that creates standing waves and increased amplitudes in portions of the concrete mass. The resulting radius of action may be increased in this way. The transmission of vibrations in the form structures may work similarly.

Frame- or gang-mounted internal vibrators are used on concrete paving machines at maximum spacing of approximately 18 in. (460 mm) at paver speeds up to 13 ft/min. (4 m/min.) for concrete consistencies of 1 to 2 in. (25 to 50 mm) slumps. Overlapping of the compression waves produces an improved consolidation effect when several vibrators are used simultaneously (Fig. 4.11). Frame-mounted internal vibrators have been used at large concrete constructions (Petrov and Safonov 1974).

Very stiff mixtures with high coarse aggregate contents and low cement contents, such as those used in mass concrete construction, require large-size, heavy-duty internal vibrators. These large-diameter vibrators have lower optimum frequency than regular internal vibrators. In this case, it seems likely that the consolidation is accomplished through a combination of acceleration and dynamic pressure generated by the vibrator.

4.4.2 *Surface vibration*—Surface vibration, illustrated in Fig. 4.12, can be accomplished by comparatively light, single, or double vibrating screeds that can consolidate up to 8 in. (200 mm) thick layers of flowing to plastic concrete. For such screeds, a frequency range of 3000 to 6000 vibration/min. (50 to 100 Hz) and accelerations of 5 to 10 g (49 to 98 m/s^2) are customary. The amplitude distribution along the screeds should be reasonably uniform. For stiff mixtures, heavier screeds are necessary to obtain the required compaction and depth effect. The compaction effort depends mainly on the dynamic stresses generated in the concrete, and can be calculated by Eq. (4-14) according to Walz (1960)

$$\text{compaction effort} = \frac{\text{static load} \times \text{amplitude} \times \text{frequency}}{\text{rate of travel}} \qquad (4\text{-}14)$$

Experience has shown that for the same acceleration, the high-amplitude/low-frequency combination is preferable over a low-amplitude/high-frequency combination.

Vibrating screeds used on thick concrete layers require a minimum width to produce the necessary depth effect.

Surface consolidation of stiff concrete with vibrating rollers is described in ACI 309.5R. Roller-compacted, zero-slump concrete, or rollcrete, has been used in dam constructions and foundations (ACI Committee 207 1980; Cannon 1972; Andriolo et al. 1984; Anderson 1983). A properly proportioned mixture is of primary importance. A mixture that is too stiff will not consolidate fully; concrete that is too wet will cause the roller to become mired in the fresh concrete. If the mixture is properly designed and contains an adequate paste volume, then fully consolidated concrete will exhibit plasticity, and a discernible pressure wave will be detected in front of the roller, particularly after two or more plastic layers have been placed. If the paste content is insufficient to fill all the aggregate voids, there will be rock-to-rock contact, and some crushing of the aggregate will occur under full consolidation.

The effectiveness of a vibrating roller is dependent on the mixture proportions, the thickness of the layer to be compacted, and the roller speed. The static weight is also important. Vibrating rollers in the range of 10,000 to 12,000 lb (4500 to 5500 kg) static drum weight with frequencies in the range of 1500 to 2500 vibration/min. (25 to 42 Hz) have been used to compact mass concrete (Tynes 1973). Maneuverability requirements and space limitations, however, may dictate the size of roller to be used. Small, self-propelled vibrating rollers have been used successfully to compact concrete next to vertical or sloping forms.

4.4.3 *Form vibration*—In form vibration, it is essential to distribute vibrations uniformly over as large a form surface

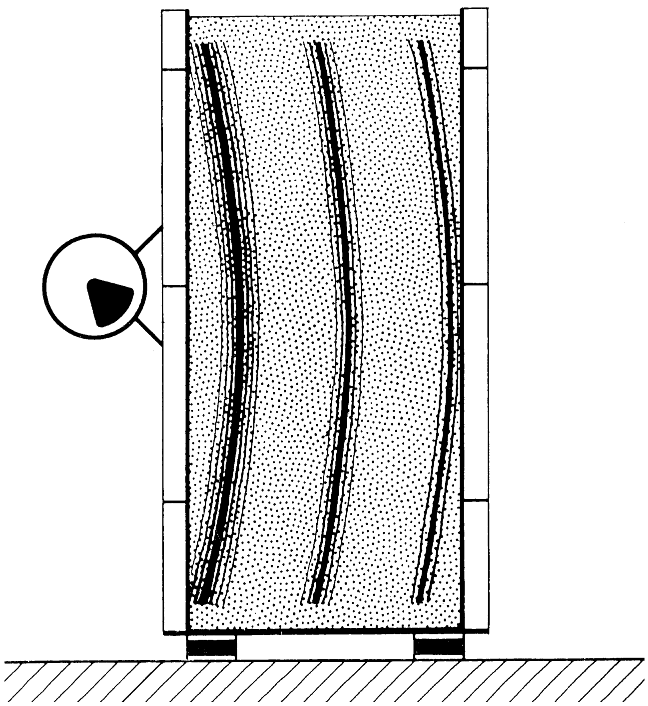


Fig. 4.13—Principle of form vibration.

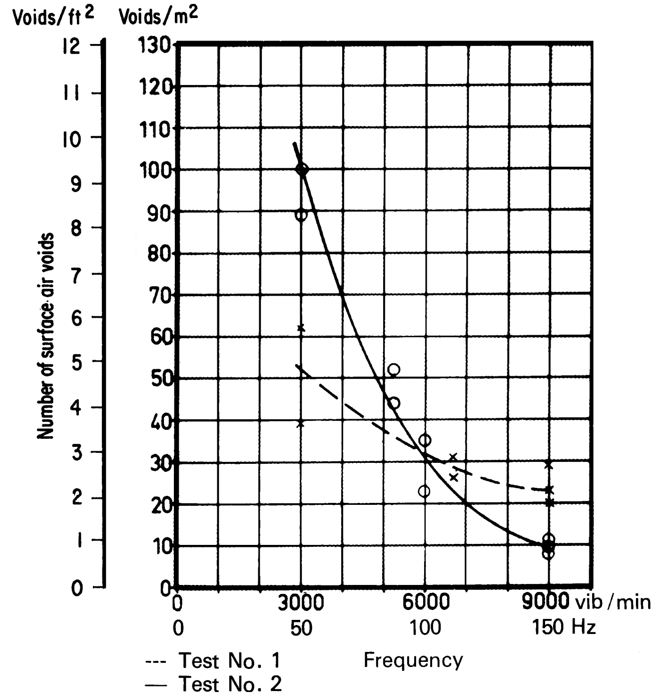


Fig. 4.14—Number of air voids in concrete surfaces obtained by form vibration at different frequencies.

as possible (Fig. 4.13). The amplitude should be fairly uniform over the entire surface. This leads to a normal maximum distance of 5 to 8 ft (1.5 to 2.5 m) between vibrators. A criterion for efficient form vibration is a minimum form acceleration of 1 to 3 g (9.8 to 30 m/s^2) for fluid to plastic mixtures when the form is filled with concrete. The corresponding acceleration for the empty form is 5 to 10 g (49 to 98 m/s^2) (Forssblad 1971).

The amplitude will decrease with increasing distance x from a plane form, according to Eq. (4-15) (refer to Section 4.3)

$$s_x = s_o e^{-(\Omega/2)x} \quad (4\text{-}15)$$

where

s_o = amplitude at the form, in. (mm).

The suitable frequency for form vibration depends to a great extent on the size and design of the forms. Large forms usually need high-frequency form vibrators to obtain the required even distribution of the vibrations over the entire form. The design of a large battery mold with a necessary vibration intensity over the full surface area is a technical problem involving the selection of proper stiffeners, vibrator brackets, and the right size, type, and placement for the form vibrators. Thus, the type and design of the form usually are more significant in the selection of low- or high-frequency form vibrators than is the type of concrete to be compacted in the form. The demand for low noise levels favors lower frequencies. Form vibration of very stiff mixtures may require a combination of high amplitudes and relatively low frequencies. Depending on specific conditions, vibration frequencies between 3000 and 12,000 vibrations/min. (50 and 200 Hz) are suitable for form vibration. High-frequency form vibration results in a better surface appearance than does form vibration at lower frequency (Fig. 4.14). The figure shows that an increase in vibration frequency reduces the number of surface voids, resulting in an improved surface appearance. This may be explained by the fact that a higher frequency creates a greater pumping effect on the fines in the fresh concrete, which accounts for the collection of fine material at the form surfaces.

4.4.4 *Table vibration*—The results of table vibration are often less consistent and more difficult to interpret than results of other vibration processes (Fig. 4.15). On a vibrating table, the forms, as well as the concrete in the forms, can move rather freely during vibration, and resonance may occur. Also, reflection of the pressure waves against the concrete surface influences the amplitude distribution, which for this reason is often irregular (Desov 1971) (Fig. 4.16).

The compaction effect is determined by the acceleration of the table. Accelerations of about 5 to 10 g (49 to 98 m/s^2) before the forms are placed on the table and 2 to 4 g (20 to 39 m/s^2) during vibration are required. In practice, accelerations higher than the minimum values based on laboratory tests are used to reduce the vibration time.

For table vibration, the optimum frequency range is fairly low: 3000 to 6000 vibrations/min. (50 to 100 Hz). Comparatively large amplitudes are needed for efficient and rapid consolidation. Given the same acceleration, a combination of high amplitude and moderate frequency results in a more rapid consolidation than does a combination of high frequency and low amplitude.

The energy formula $W = c_1 m s^2 f^3$ is also applicable for table vibration, according to Walz (1960). In a stiff fresh concrete, low vibration intensity can be compensated for by

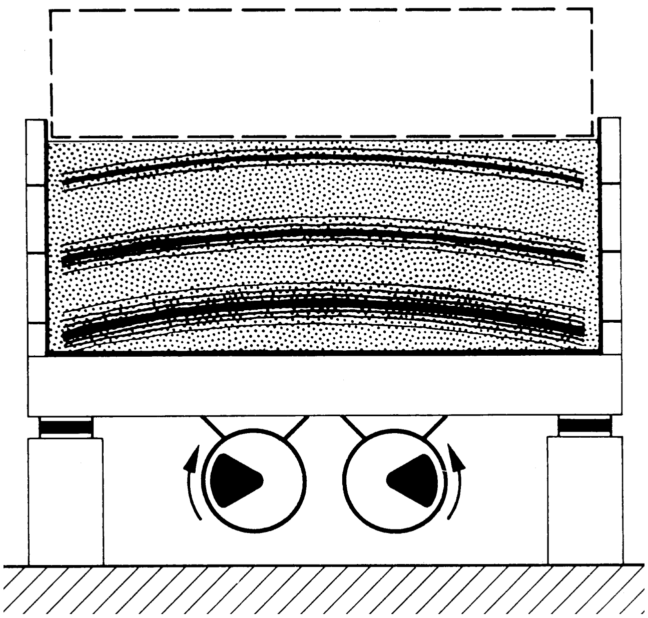


Fig. 4.15—Principle of table vibration.

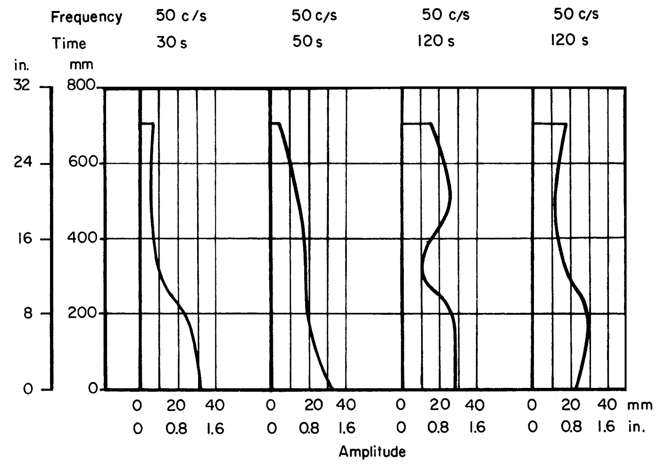


Fig. 4.16—Amplitude distribution in concrete on vibrating table at different frequencies and times of vibration.

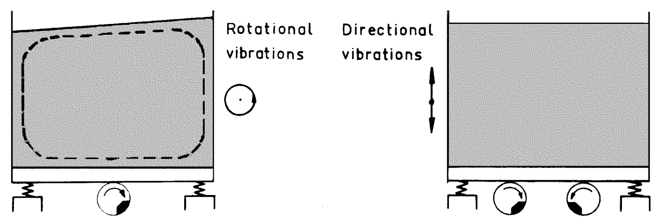


Fig. 4.17—Rotational and directional vibratory motions.

a longer vibration time. The energy formula indicates that the influence of the amplitude is greater than that of the acceleration. This is in accordance with test results and field experience.

The question of whether concrete forms should be rigidly attached to the table or placed loosely was investigated by Strey (1960). Loose placement resulted in a product of higher strength and density. The difference, however, was quite small, and was probably affected by the higher accelerations resulting from the impact between the forms and the table. The vibration time could also be shortened with loose forms. The noise level, however, is lower with the form rigidly connected to the table.

Davies (1951) has studied the influence of the direction of table vibrations. Using concrete mixtures of very stiff consistency, a circular vibratory motion of the table in a vertical plane produced 10% higher concrete strength than did a horizontal circular vibratory motion. A decrease of 10 to 15% in strength was obtained with vertically directed vibrations compared with vertical circular vibrations (Fig. 4.17). With fluid to plastic mixtures, these differences are less pronounced. A vertically directed vibratory motion is, in many cases, preferred because the movements of the concrete mass are reduced compared with those caused by a circular vibratory motion.

For table vibration, a static load is sometimes applied to the concrete surface. In this way, the increased dynamic pressure benefits consolidation of dry and stiff mixtures. Excessively high static loads dampen the vibratory movement of the concrete particles, thus reducing consolidation. Best results can be attained by applying a combination of vibration and a moderate static pressure. By gradually increasing the pressure, the concrete mass is after-compacted without simultaneous vibration.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The latest editions of the standards and reports listed below were used when this document was prepared. Because these documents are revised frequently, the reader is advised to review the latest editions for any changes.

American Concrete Institute

211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete

211.3R Guide for Selecting Proportions for No-Slump Concrete

237R Self-Consolidating Concrete

238.1R Report on Measurements of Workability and Rheology of Fresh Concrete

309.5R Compaction of Roller-Compacted Concrete

ASTM International

C187 Test Method for Normal Consistency of Hydraulic Cement

C1170 Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table

The above publications may be obtained from the following organizations:

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

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

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Report on Behavior of Fresh Concrete During Vibration