Behavior of Fresh Concrete During Vibration

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This report covers the stateof the art of processes that take place in the consolidation of fresh concrete during vibration These processes, theological and mechanical in nature, are discussed to provide better understanding of the principles. The first chapter presents the historical developments relative to consolidating concrete. The second chapter deals with the rheological behavior of concrete during consolidation and the associated mechanisms of dynamic compaction. The third 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 concretes; hardening; history; mechanical impedance; mix proportioning; reviews; **rheological properties;** stability; **vibration;** vibrators (machinery).

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CHAPTER l-HISTORY OF CONCRETE VIBRATION

At the turn of the 20th century, concrete mixtures were generally placed very dry. The material was deposited in shallow lifts and rammed into place by heavy tampers, which involved hard manual labor. Large, open sections containing little or no reinforcement, such as foundations, retaining walls, and dams were typical. Many of these structures are still in service, proving that this type of construction produced strong, durable concrete.

Later, reinforced concrete became a common construction method. Thinner structural sections were consequently designed. Constructors found the dry mixtures could not be tamped in the narrow forms filled with reinforcing steel and, as a consequence, mixtures became wetter. When it was discovered that mixtures could be transported by inclined chutes, the slump was further increased.

It then became apparent that these wet mixtures were not producing good concrete. The result was lower strength, durability failures, drying shrinkage, and increased cracking.

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ACI 309.1R-93 supersedes ACI 309.1R-81 (Revised 1986) and became effective March 1, 1993. Revisions to this report were submitted to letter ballot of the committee, which consists of 15 members; ballot results were 11 affirmative!, no negatives, no abstentions, and 4 ballots not returned. Minor revisions have been made to the report. Additional references have been added. The revisions have been successfully balloted by ACI Committee 309 and processed in accordance with Institute procedures. The 1986 revision added nine references to provide more up-to-date sources of information. Also, several minor editorial corrections were made. The 1992 revision added five additional references to provide more up-to-date sources of information.

The water-cement ratio concept, expounded about 1920, demonstrated that the quality of concrete dropped rapidly as more water was added to the mixture.

Methods other than tamping were tried to consolidate the stiffer concrete. Compressed air was introduced into the fresh concrete through long jets.

Around 1930, machines were developed to impart vibratory motion to concrete.

In 1936, an ACI Committee 609 report* described the benefits of vibrators but failed to explain the interaction between a vibrator and fresh concrete. The frequencies of the early vibrators were limited to 3000-5000 vibrations per min (50-80 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.

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

In 1953, Meissner summarized previous research studies and reviewed the state of the art on available equipment and its characteristics.

A 1960 ACI Committee 609 report gave recommendations for vibrator characteristics applicable to different types of construction and described field practices.

In 1960, Walz described the various types of vibrators: internal, surface form, and table-and their application. He also showed that the reduction in internal friction is primarily the result of acceleration produced during vibration.

This was followed in 1962 by Rebut's discussion of the theory of vibration, including the forces involved, the types of vibrators and their application to different classes of construction, and vibration measuring devices.

Also in 1962, Ersoy published the results of extensive laboratory investigations on the consolidation effect of internal vibrators. He varied the concrete consistency, size and shape of form, and vibration parameters. Ersoy concluded that the eccentric moment, weight of the eccentric times its eccentricity, and frequency are the important factors for determining the consolidation effectiveness of an internal vibrator.

In 1963, a conference on vibration was held in Budapest, Hungary, where the following notable papers were given:

1. Kolek (1963) describedvibration theories, formulas, and experimental work aimed at a better understanding of the processes involved. He also gave an explanation of the process of consolidation, assuming it occurred in two stages: the first comprised the major subsidence or slumping of the concrete; the second involved deaeration (removal of entrapped air).
2. 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 applied to the concrete, amplitude of vibration, and the number of vibrations transmitted to the concrete were found to be the most important factors affecting the degree of consolidation.

In 1964, Murphy 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, Kirkham, Kolek, and Plowman on the subject of consolidation were particularly noteworthy.

In 1965, Forssblad 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 surface of the concrete.

Some observations were made on the effect of air entrainment introduced in the late 1940s on concrete consolidation. Air entrainment making the mixture more cohesive enhances particularly lean mixtures deficient in fines as well as mass concrete. Reading observed in 1967, 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.

In 1968, Ritchie reviewed such concepts as workability and described such factors as stability, compactability, and mobility and corresponding methods of measurements.

Ultrahigh frequency vibration has been investigated in the Soviet Union by Shtaerman (1970). He reported that ultrahigh frequency vibration increases the hydration of the cement and improves the properties of concrete. However, high energy input and heat generation, and the small depth of penetration of the vibration, are practical drawbacks to this method.

Also, in 1970, Wilde 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. In the early 70s, Csutor (1974) developed a method for calculating the pressure required to produce the same consolidation regardless of the type of vibrator used.

In 1972, a recommended practice for consolidation of concrete by ACI Committee 309 was published. This paper 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 (University of Leeds) held in 1973 included papers by Ahmad and Smalley, Bache, Popovics, and others dealing with theological properties and consolidation of concrete.

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

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

In 1976, Taylor published the results of extensive laboratory tests on the effect of different parameters on the effec-

* See list of cited references in Section 4.2.

tiveness 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.

In 1977, Alexander 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.

There have been a number of studies on the effects of revibration. Tuthill summarized present knowledge of this subject in 1977. Revibration may produce benefits, particularly for the wetter mixtures, in eliminating water gain under reinforcing bars, reducing bugholes, especially in the upper portion of deep lifts, all of which increase the strength of the concrete.

In 1984, Winn, Olsen, and Ledbetter 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. The symposium documents were published in 1987. Papers relating to the behavior of fresh concrete during vibration included:

1. Forssblad (1987) reported on the need for consolidation of flowing concrete mixtures and how these mixtures responded to internal, surface and form vibration.
2. Harrell and Goswick (1987) reported on the concurrent use of internal and external vibration to obtain superior consolidation in tunnel concrete.
3. Kagaya, Tokuda and Kawakami (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 normal weight 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.
4. 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 a degree of consolidation of 97 percent or more.
5. 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 insure that low slump concrete can be placed successfully. However, a better understanding of the interaction of vibration and fresh concrete is still desirable.

CHAPTER 2-INFLUENCE OF RHEOLOGY ON CONSOLIDATION OF FRESH CONCRETE

2.1-Rheology of fresh concrete

Rheology is the science that deals with the flow of materials and includes the deformation of hardened concrete, handling and placing of freshly mixed concrete, and the behavior of slurries and pastes. For purposes of this discussion, only the rheological properties of fresh concrete are considered.

In concrete work, it is usually desirable to produce the highest practical and economical density. Toward 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 by a number of investigators attempt to define the parameters involved (Lassalle 1980). 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 penetration, and other remolding and deforming tests. These tests, interpretation of their results, and rheology of fresh concrete are discussed by Popovics (1982).

Ritchie (1968) subdivides rheology of fresh concrete into three main parameters: stability, compactibility, and mobility, as shown in Fig. 2.1.

Although the diagram points out primary factors, it does not show any relationship between categories. For example, viscosity, cohesion, and the angle of internal resistance may affect mixture stability and compactibility. Ritchie's work can be summarized as follows.

2.1.1 *Stability*-Stability is defined as the flow of fresh concrete without applied forces and is measured by bleeding and segregation characteristics. Bleeding occurs when the mortar is unstable and releases free water. 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 is defined as a mixture's instability, caused by a weak matrix that cannot retain individual aggregate particles in a homogeneous dispersion. Segregation is possible under both wet and dry consistencies. Wet segregation occurs when the water content is such that the paste cannot hold the aggregate particles in position while the concrete is transported and compacted. Conversely, dry segregation takes place where concrete of low water content results in a "crumbly" mixture during handling. If manipulation can be minimized, these crumbly mixtures are often satisfactory and quite stable once they are consolidated. When concrete is vibrated, the matrix becomes momentarily fluid and develops cohesion and shear resistance. Ritchie in-

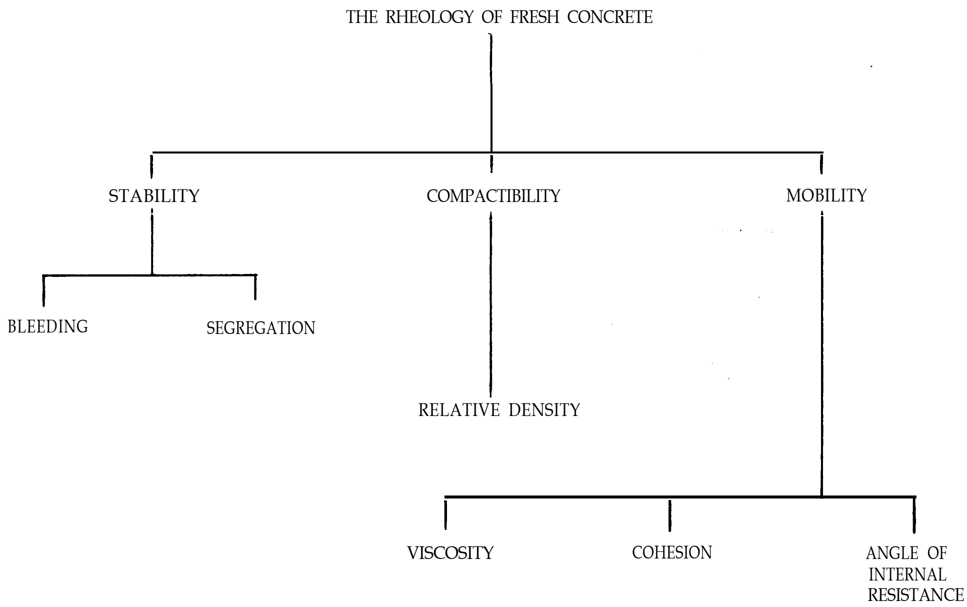


Fig. 2.1-Parameters of the rheology of fresh concrete

dicates a definite link between cohesion and resistance to segregation.

2.1.2 *Compactibility*-Compactibility measures the ease with which fresh concrete is compacted. Compacting consists of expelling entrapped air and repositioning the aggregate particles in a dense state without causing segregation.

The compacting factor test, covered by British Standard BS 1881, is designed to measure compactibility. Although the test has a wide range of applications, it has some limitations. Cohesive mixtures stick in the hoppers of the test apparatus and mixtures with low to very low workabilities produce wide variations in results. Because of these variations, Cusens (1955 and 1956) has suggested a vibrated compacting factor test for comparing mixtures of low workability.

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 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 l-in. diameter (25 mm) internal vibrator. These two readings plus the values obtained from the standard compacting factor test give an indication of the relative ease it takes to change a mixture from its loose to its 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.

2.1.3 *Mobility*-Both Ritchie (1968) and Bache (1973) discuss mobility of fresh concrete in terms of its viscosity, cohesion, and internal resistance to shear. The interaction between rheology and the stresses caused by vibratory consolidation is shown by Bache in a number of examples. He states flow is restricted by frictional, cohesive, and viscous forces. Cohesion develops due to attractive surface forces between particles while resistance is caused by the viscous flow of the matrix. When increasing the shear stresses below the yield value, no flow occurs, and the concrete behaves like a solid. At higher oscillating stresses, the bond strength between particles becomes insufficient to prevent flow, and at the same time the viscosity gradually decreases. Concrete mixture proportioning, therefore, indirectly takes into account that the viscosity of the lubricating cement paste can be adjusted to the vibratory stress and its frequency. It follows that with increased vibratory or consolidation pressure an increase in paste viscosity is required, i.e., a decrease in the water-cement ratio and/or increased frequency of vibration.

The momentum transport, as Bache calls the transmission of mechanical stresses on fresh concrete, is defined by such parameters as elasticity, cohesion, friction, viscosity (shear and bulk), density, damping, and sound velocity.

The graph in Fig. 2.1.3a illustrates the various phases of flow under applied stresses. At low stresses, the material behaves as a solid of extremely high viscosity. As stresses increase, concrete behavior gradually changes to that of a liquid.

As conceived by Ritchie, the viscosity of the matrix contributes to the ease with which the aggregate particles can move and rearrange themselves within a mixture. To achieve a better understanding of a mixture's flow characteristics, it is important to be able to measure the initial viscosity of the cement paste fraction of the mixture and to study its stiffening with time.

Cohesion is defined by Ritchie (1968) as the force of adhesion between the matrix and the aggregate particles. It pro-

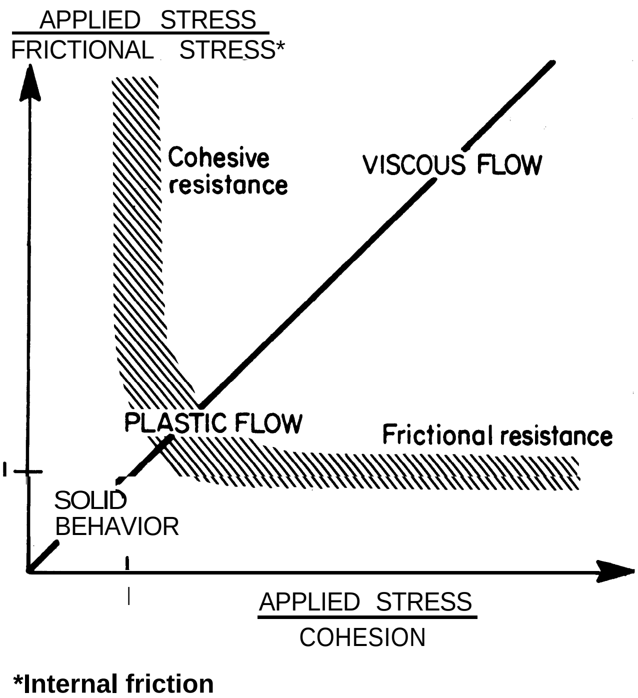


Fig. 2.1.3a-Flow of concrete under various types of stress

vides the tensile strength of fresh concrete that resists segregation and is measured by a direct tension test, which was first used by Hallstrom (1948).

Internal friction occurs when a mixture is displaced and the aggregate particles translate and rotate. The resistance to deformation depends on the shape and texture of the aggregate, the richness of the mixture, the water-cement ratio, and the type of cement used. The friction resistance of the mixture can be determined by the triaxial test as discussed by Ritchie (1962). Thus, the angle of internal friction plays an important part in the mobility of a concrete mixture.

To summarize, Ritchie's approach to the rheology of concrete includes the parameters of stability, compactibility, and mobility, which are necessary to determine the suitability of any mixture. Stability is measured by bleeding and segregation tests. Compactibility is established by the extended compacting factor test. Mobility is evaluated by the laboratory triaxial compression test. Relative mobility characteristics, according to Ritchie, can be measured at the construction site by using the Vebe test in conjunction with the basic compacting factor test.

A somewhat similar approach to rheology is suggested by Reiner (1960), who also considers workability and stability important rheological properties of fresh concrete. Reiner correlates workability with four tests designed by Herschel and Pisapia (1936). These tests determine properties which are considered to be partially independent of each other: harshness, segregation, shear resistance, and stickiness. Harshness is measured by the spread of concrete on a flow table after a certain number of drops; segregation is measured by the amount of mortar separated from concrete by jolting on the flow table; shear resistance is measured in the shear box first evolved by Terzaghi and later developed by Casagrande for soils; and stickiness is measured by the vertical force required to separate a horizontal steel plate from the surface of a freshly made concrete.

Reiner uses Forslind's (1954) definition of stability as a condition in which the aggregate is completely separated by the paste, and a random sampling shows the same particle size distribution during transportation, placing, and compacting.

Reiner and a number of more recent investigators have discussed the rheological properties of concrete in terms of the "Bingham" model. The Bingham model is based on a mathematical relationship proposed by E.C. Bingham (1933). In this model, the shear stress of a material is expressed in terms of its cohesion, plastic viscosity, and the rate at which the shear load is applied, as shown in Fig. 2.1.3b where v indicates the cohesion of the material and μ indicates its plastic viscosity. To establish a straight line, at least two points are needed. Accordingly, the workability of concrete cannot be defined by a test that produces only a single point.

Tattersall (1976) directed work to mobility characteristics measured by a single test. The procedure is based on determining the power required to mix concrete at various speeds and then calculating the torque by dividing the power by the speed. The torque for a given mixture reportedly varies linearly with the mixing speed and can be expressed as $T = g + hN$, where T is the torque measured in N rps, and g and h are constants which are proportional to the cohesion and the plastic viscosity, respectively, of the mixture.

Future studies by Tattersall will evaluate desirable combinations of g and h for various conditions. Since this problem is complex, large populations of test data will be required

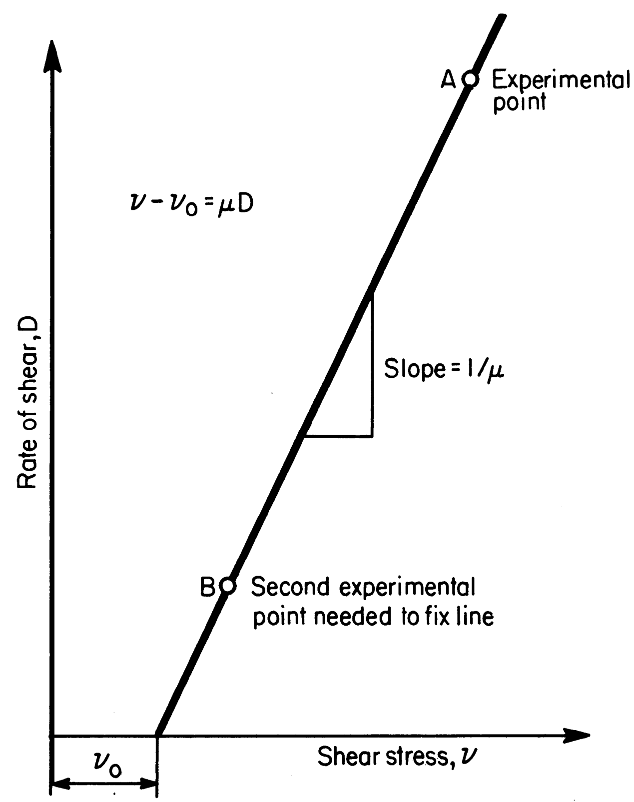


Fig. 2.1.3b-The Bingham model

for definitive conclusions. Tattersall found, however, that two mixtures with identical values of *g* and *h* will also have identical values for consistency, compacting factor, and Vebe time. On the other hand, when these values differ, two mixtures may show similarity in any one of the three standard tests, but will behave differently in the other two. The significance of Tattersall's work is that test data can be provided at two or more points (shear conditions) by a single test method. Previous test methods have been based upon single point tests (single test condition), and therefore had to be used in combination with other tests to achieve a better understanding of concrete rheology. For example, the Vebe test was previously cited for use with the compacting factor test to measure mobility and compactibility.

2.2-Rheology in practice

The rheological properties or workability of a concrete mixture are affected by mixture composition and the amount of each constituent, properties of the ingredients (especially particle shape, maximum size, size distribution, porosity, and surface texture of the aggregate), and the presence of admixtures, the amount of mixing, and the time elapsed following mixing.

2.2.1 *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:

a) "Recommended Practice for Selecting Proportions for Normal and Heavyweight Concrete (ACI 211.1)."
b) "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2)."
c) "Recommended Practice for Selecting Proportions for No-Slump Concrete (ACI 211.3)."

A concrete mixture with an excessive coarse aggregate content lacks sufficient mortar to fill the void system, resulting in a loss of cohesion and mobility. Such mixtures are termed "harsh" and require a great deal of effort to place and compact. Strength and impermeability of harsh mixtures, even at maximum density, will be less than those for a properly proportioned mixture. Harsh mixtures can also be caused by a low air content; an increase in air may alleviate the excessive use of fine aggregate. On the other hand, excessive amounts of fine aggregate or entrained air in a concrete mixture greatly increase the cohesion and cause the mixture to be sticky and difficult to move, The greatest effect, however, of a high fine aggregate content is an increase in surface area of particles within the mixture, which increases the amount of water required to coat these surfaces. This in turn can result in increased drying shrinkage and cracking. Unless the cement content is increased to maintain a constant water-cement ratio, the mixture with excessive fine aggregate will also have less strength. The current practice is to proportion concrete mixtures with an excess of fine aggregate and to use more cement than would be necessary for a concrete mixture of optimum fine aggregate content.

The cement content also affects the workability of a concrete mixture. High cement content mixtures are generally sticky and sluggish, particularly in the normal range of slump for cast-in-place concrete. Furthermore, the lower water-cement ratio and higher content of hydrating material reduce the workability of rich mixtures from that measured immediately after initial mixing.

2.2.2 *Consistency*-The consistency of concrete, as measured by the slump test, is an indicator of the relative water content of the concrete mixture. An increase in water content or slump above that needed to achieve a workable mixture produces greater fluidity and decreased friction. More significantly, the additional water increases the water-cement ratio and has the undesirable effect of reducing the cohesion within the mixture and increasing the potential for segregation and excessive bleeding. It is common to use more water than needed, assuming that the rheological properties are thus improved; in fact, this practice produces results to the contrary. Likewise, too low a slump or water can result in equally undesirable properties of a concrete mixture by loss of mobility and of compactibility and can cause unnecessary delay and difficulty during placement and consolidation. An increase of 1 percent air is equivalent to an increase of 1 percent in fine aggregate or increasing the unit water content by 3 percent. An excessively dry mixture may also result in loss of cohesion and "dry segregation."

2.2.3 *Hardening and stiffening*-Rapid loss of workability can be associated with elevated concrete temperature, use of high early strength cement, cement deficient in gypsum, and use of accelerating admixtures, all of which increase the rate of hardening. Dry, porous, or friable aggregates will rapidly reduce workability by absorbing water from the mixture or by increasing the surface area to be wetted. Use of cement with false setting tendencies can cause premature stiffening and an almost immediate loss of workability unless the mixing time can be extended to restore mixture plasticity. The interaction of various chemical admixtures or chemical compounds present in a concrete mixture can accelerate the hardening rate or cause other reactions which also may reduce the workability. In cases where loss of workability occurs, it is essential to transport, place, and compact the concrete as rapidly as possible. Addition of water to restore the consistency will generally reduce the quality of the finished product.

2.2.4 *Aggregate shape and texture*- Aggregate particle shape and particle size distribution are generally recognized as significant factors influencing the rheology of concrete. Accordingly, ACI 211.1 takes these factors into consideration for trial mixture proportioning. The coarse aggregate, dry-rodded unit-weight method provides a factor based on voids in the coarse aggregate which, when used in conjunction with the fineness of the fine aggregate fraction, will provide a reasonable coarse and fine aggregate content for workability. The unit weight of the coarse aggregate is a function of the particle shape and size distribution. The unit weight of rough, highly angular particles will be less than that of smooth, well-rounded particles of the same density because of the particle friction and interference. Thus, the percentage of voids to be filled by mortar will be greater, requiring higher fine aggregate contents and correspondingly higher water contents for angular to subangular coarse aggregates. Similarly, angular fine aggregate will increase internal friction in the concrete mixture and will require higher water contents than well-rounded natural sands to produce a given workability. Several studies have shown the effects of aggregate angularity and have provided means of measuring angularity or reducing it to an index number that can be correlated to a compactibility factor (Hughes 1966; Kaplan 1958; Lees 1964; Murdock *1968).*

2.2.5 *Aggregate grading*-The general consensus is that the concrete aggregate must be well-graded to achieve good workability. The absence of a particular size of aggregate (gap-graded) or a change in the size distribution may have an appreciable effect on the void system and workability. Generally, such effect is greater in the fine aggregate than in the coarse aggregate fraction. As the fine aggregate becomes finer, the water requirement increases and the concrete mixture becomes increasingly sticky. As the fine aggregate fraction becomes coarser, cohesion is reduced, the mixture becomes harsh, and the tendency for bleeding increases. Adjustment of the grading or fine aggregate content will be necessary to maintain workability as the above mentioned changes occur.

2.2.6 *Maximum aggregate size*-Improved concrete quality can generally be realized by increasing the maximum size of the coarse aggregate. Such an increase will reduce the fine aggregate content required to maintain a given workability, and will thereby reduce the surface area to be wetted and the cement content necessary for a constant water-cement ratio.

2.2.7 *Admixtures*-- The presence of chemical or mineral admixtures will affect the rheological properties of a concrete mixture. Some chemical admixtures will improve workability and pumpability at a given slump. Accelerators or retarders will reduce or extend the workability time of a given mixture. Air-entraining admixtures increase the cohesion and reduce the tendency for bleeding of a concrete mixture. Mineral admixtures such as pozzolans, and in particular fly ash, may improve the workability and generally reduce bleeding. Some high-range water-reducing admixtures can be used strictly as water-reducing admixtures to obtain the benefits of a low water-cement ratio or to temporarily increase the consistency of a concrete mixture without producing many of the adverse effects generally associated with wet mixtures. Properly proportioned concrete mixtures containing high-range water-reducing admixtures generally retain their stability even at high slump.

2.2.8 *Mixture adjustments*-To optimize the workability of a particular concrete mixture, it is essential to make adjustments as the properties of the materials and the field conditions change. It should never be assumed that trial mixture proportions are the final proportions for use in the field. Changes in the rheological properties of concrete will often be detected visually. Where significant deficiencies appear, mixture adjustments are warranted. Proper attention to the rheological properties of a mixture can effectively reduce construction and material costs.

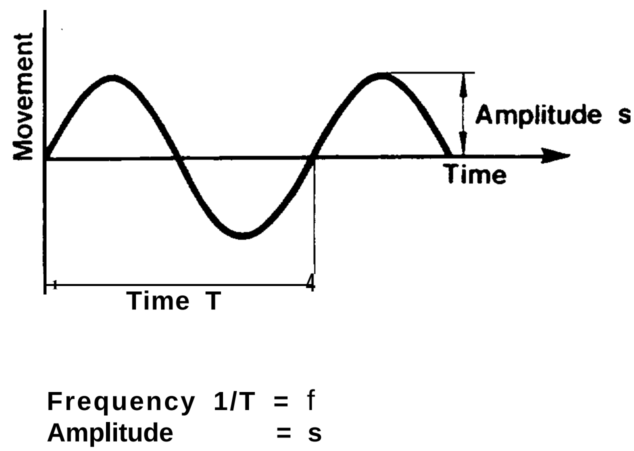


Fig. 3.2. 1-Sinusoidal vibratory motion

2.3-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 (Ahlsen 1979).

CHAPTER 3- MECHANISMS OF CONCRETE VIBRATION

3.1—Introduction

Vibration has been used for practically 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).

3.2-General

3.2.1 *Vibratory motion*- Concrete vibrators generally use a rotating eccentric weight. Such vibrators generate harmonic motion, characterized by a sinusoidal wave form used for mathematical analysis. (See Fig. 3.2.1).

Sinusoidal oscillation is defined by the equation:

$$x = s \sin \omega t = s \sin 2\pi f t$$

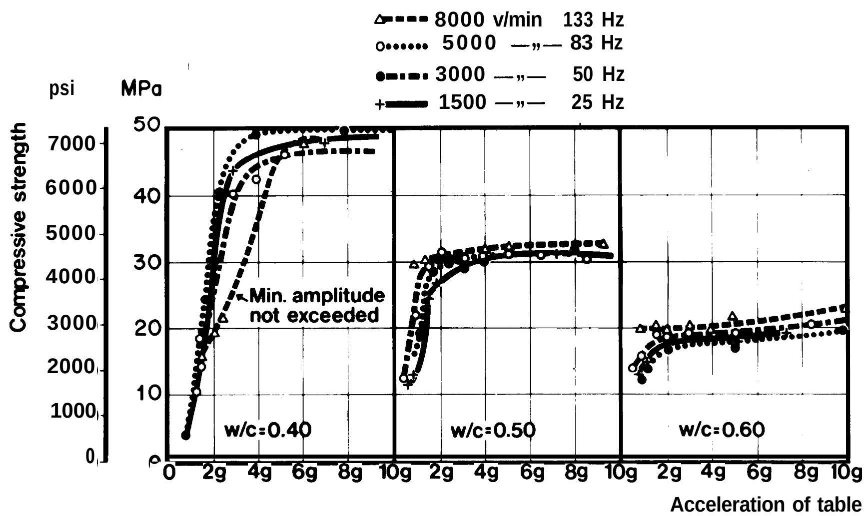


Fig. 3.3a-Correlation between compressive strength of the hardened concrete and acceleration during vibrating. Tests on vibrating table

where

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

From this equation, the following relationships are obtained:

$$\dot{x} = 2\pi f s \cos 2\pi f t = v \cos 2\pi f t$$

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

$$\ddot{x} = 4\pi^2 f^2 s \sin 2\pi f t = a \sin 2\pi f t$$

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

3.3-Parameters of concrete vibration

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

Fig. 3.3a indicates that consolidation of fresh concrete starts at an acceleration of about 0.5 g (4.9 m/sec^2). The compaction effect then increases linearly to an acceleration between 1 g and 4 g (9.8 and 39.2 m/sec^2), depending on the consistency of the concrete. A further increase in acceleration does not increase the compaction effect.

The left diagram in Fig. 3.3a 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) has been 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. 3.3.a. Table 3.3 shows that the strength of the hardened concrete will be mainly independent of frequency and amplitude as long as the minimum acceleration is exceeded.

Forssblad (1965b) has shown efficient vibratory compaction of moist soils when dynamic pressure forces were of the magnitude 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. Forssblad (1978) suggests that this same criteria be valid for stiff concrete mixtures.

During vibratory consolidation, energy transmitted to the concrete is another important parameter. The energy can be calculated according to the following formula, postulated by Kirkham (1962).

$$w = c_1 m s^2 f^3 t$$

where

W = energy, ft-lb (J)
c_1 = constant, depending on stiffness and damping in the concrete
m = concrete mass, $\frac{lb}{32.2\ ft/sec^2}$ $\left(\frac{kg}{9.81\ m/sec^2}\right)$
S = amplitude, in. (mm)
f = frequency, cpm (Hz)
t = time, sec

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

Table 3.3-Compressive strength and density of concrete specimens vibrated with internal vibrators at various frequencies and amplitudes

	Specimen													Coefficient of Variation. Percent
		2	3	4	5	6	7	8	9	10	11	12	Mean	
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/ft³ (kg/m³)	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
At9500 cpm and 0.047in.(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/ft³ (kg/M3)	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/ft³ (kg/m³)	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)	±11
density, lb/ft³ (kg/m³)	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)	±11

3. Minimum vibratory amplitude for any given mixture
4. Minimum vibratory energy for all mixtures

3.3.1 *Wave transmission through fresh concrete*-The transmission of a sinusoidal compression wave through an elastic medium is expressed by the formula:

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

where

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

The maximum pressure p generated during the transmission of a sinusoidal compression wave is calculated according to the formula

$$p = vcy$$

where

v = maximum particle velocity, in./sec (mm/sec)
c = wave velocity, ft/sec (m/sec)
y = 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 following relationships exist:

$$c = \lambda f = \frac{E}{\gamma}$$

where

λ = wave length, ft (m)
f = frequency, Hz
E = dynamic modulus of elasticity, psi (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/sec (45 in./sec) according to Halken (1977). Wave velocities between 200 and 800 ft/sec (60 and 250 in./sec) have been reported for vibration periods of 1 to 2 min. An average value of 500 ft/sec (150 m/set and a frequency of 200 Hz correspond to a wave length of 2.5 ft (0.7 m). Laboratory tests conducted by Halken established a value of 500 psi (3 MPa) for the dynamic modulus of elasticity of fresh concrete.

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

Transmission from the state of rest to the fluid vibrating state has been shown schematically by Bergstrom (1949). (See Fig. 3.3.2a). Kolek (1963) has 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 de-aeration 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) has investigated the vibration process by measuring the mechanical impedance (See Fig. 3.3.2b). At

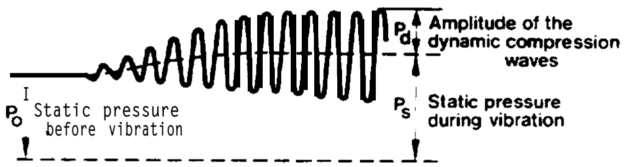


Fig. 3.3.2a- Transmission through vibration from the state of rest to the fluid state

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. After transformation, the vibratory motion was controlled by the mass forces with little or no effect from stiffness or damping indicating that the concrete during vibration behaves like a fluid. Since

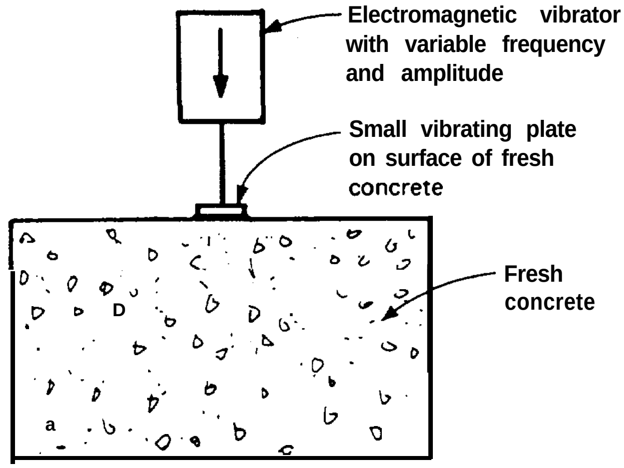


Fig. 3.3.2b- Impedance test

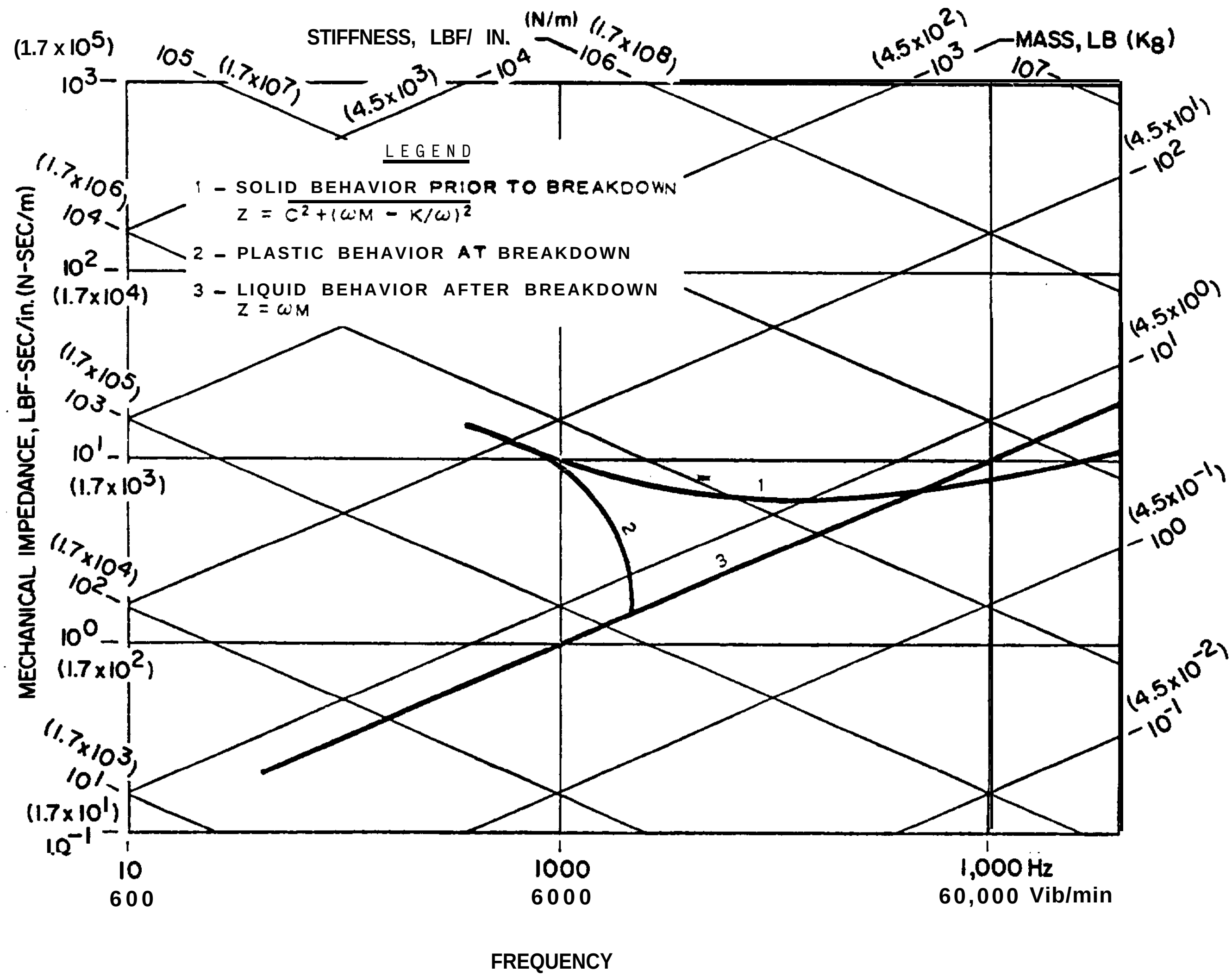


Fig. 3.3.2c-Three types of behavior of the fresh concrete

inertia is the primary hindrance to motion, Newton's second law of motion can be applied:

$$F = ma$$

where

F = force, lbf (N)

m = mass, $\frac{}{32.2\ ft/sec^2}\left(\frac{kg}{9.81\ m/sec^2}\right)$

a = acceleration, in./sec^2 (mm/sec^2)

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

Fig. 3.3.2c 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 equal to

$$Z = \sqrt{C^2 + (\omega M - K/\omega)^2}$$

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 had tracked down one of the lines slanting to the right, it would indicate that the system being vibrated was pure stiffness. If the impedance had tracked across one of the horizontal lines, then the system being vibrated would have been a pure damper. All combinations are possible, and most physical systems consist of all three mechanical elements: masses, springs, and dampers.

Since 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.

Also, the fluid mixture has no reasonant frequency. Note that Alexander's 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) has suggested the application of hydrodynamic theories based on the bubble movements in the fresh concrete. Studies on the same subject have also been 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 must be avoided.

Bache (1977) also discussed the stability of freshly compacted concrete. This stability is dependent on internal friction, cohesion, and capillary pressure. 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.

3.3.3 *Energy consumption*-The initial rapid subsidence of the mixture during vibration can be characterized as plastic deformation requiring a large energy consumption; for complete consolidation the entire transmitted energy is consumed.

During the final de-aeration stage of vibration, no additional energy is necessary to keep the mass in motion since 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 de-aeration stage, thus requiring a limited energy supply.

3.4-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, the fresh concrete mixture, and the effect of the form must be studied (Bresson 1977).

3.4.1 *Internal vibration*-An internal vibrator immersed in fresh concrete generates rapidly recurring circular compression waves. (See Fig. 3.4.la). The wave amplitudes rapidly decrease with increasing distance from the vibrator.

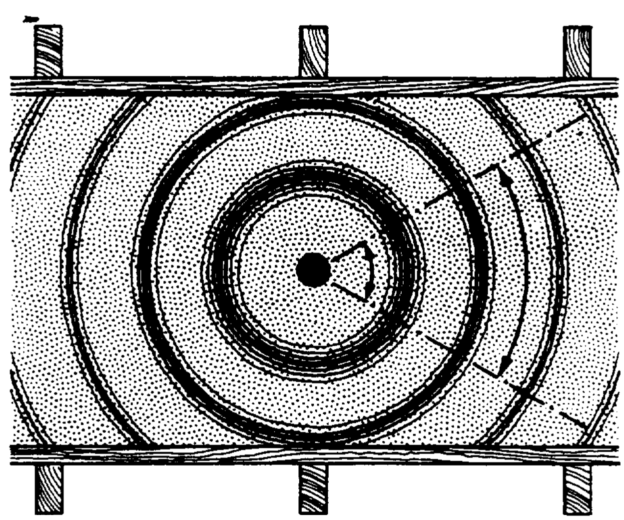


Fig. 3.4.1a-Principle of internal vibration

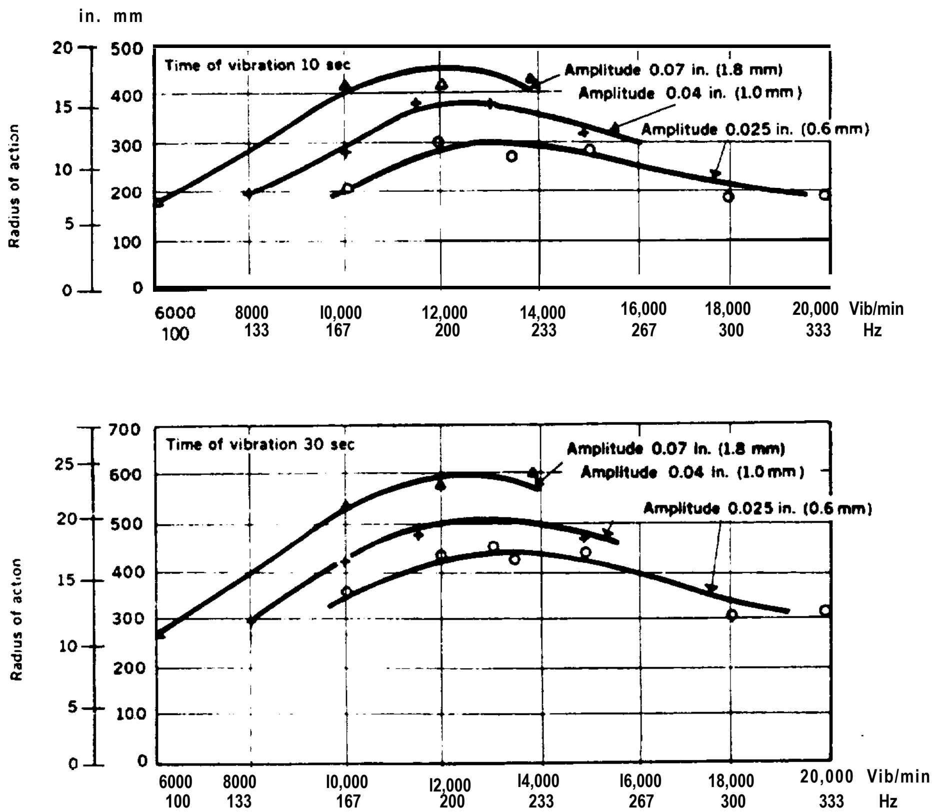


Fig. 3.4.1b- Correlation between radius of action, frequency, and amplitude for a 60 mm internal vibrator

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

Bergstrom and Forssblad 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 2½ in. (60 mm) internal vibrator after 10 and 30 sec of vibration are shown in Fig. 3.4.1b. The largest radius of action occurred at an optimum frequency of about 200 Hz (12,000 vibration/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 has been 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 in. x 8 in. x 8 in. (850 mm x 200 mm 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.

Results of research by Taylor (1976) indicate that accelerations for internal vibrations should range from 100 to 200 g (980 to 1960 m/sec^2) for concrete with maximum aggregate sixes of 1½, ¾ and ⅜ in. (38, 19, and 10 mm). For a given acceleration, an internal vibrator will show best performance at high 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, reinforcing steel, etc., 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. This is an area which needs further study.

The following factors are of interest with respect to the mechanisms of internal vibration:

1. Reduction of the amplitude of the vibrator head in fresh concrete
2. Transmission of vibrations from the vibrator to the fresh concrete
3. Geometric reduction in energy-density during circular propagation of the compression waves
4. Damping effect on wave propagation through the fresh concrete

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 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 according to Lamb (1945). According to Kolenda (1972), it is then possible to calculate the acceleration a of a cylindrical internal vibrator operating in concrete with the formula:

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

where

a = acceleration, in./sec² (mm/sec²)
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)
m_b = weight of displaced concrete, lb (kg)

The amplitude of an internal vibrator operating in concrete is approximately 70 to 75 percent of its amplitude in air indicating good agreement between calculated and measured values. (See Fig. 3.4.1c).

The centrifugal force *F*, which sometimes is used as a parameter of an internal vibrator, is calculated according to the equation:

$$F = 4(\pi f^2) m_e r \frac{1}{8}$$

where

F = centrifugal force, lbf (*N*)
g = acceleration, ft/sec² (m/sec²)

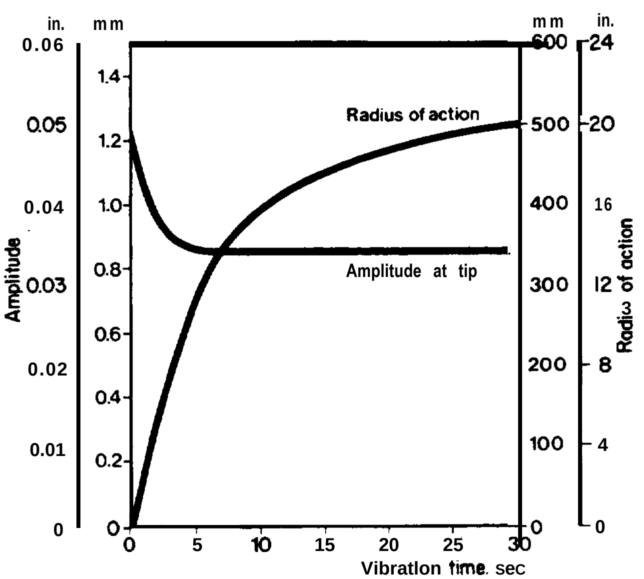


Fig. 3.4.1 c-Amplitude and radius of action of internal vibrator

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

$$P_c \geq 1.0 + \gamma g h - 0.03$$

Atmospheric pressure, MPa; Hydrostatic pressure, MPa; Vapor pressure, MPa

where

γ = density, lb/ft³ (kg/m³)
g = acceleration due to gravity (m/sec²)
h = depth below surface, ft (m)

Kolenda (1972) has developed curves for internal vibrators of different diameters, which show combinations of frequencies and amplitudes which should not be exceeded if cavitation is to be avoided. See Fig. 3.4.ld.

The geometrical energy distribution due to the radial generation of compression waves, as well as the damping, can be calculated according to the formula postulated by Dessoff (1937):

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

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

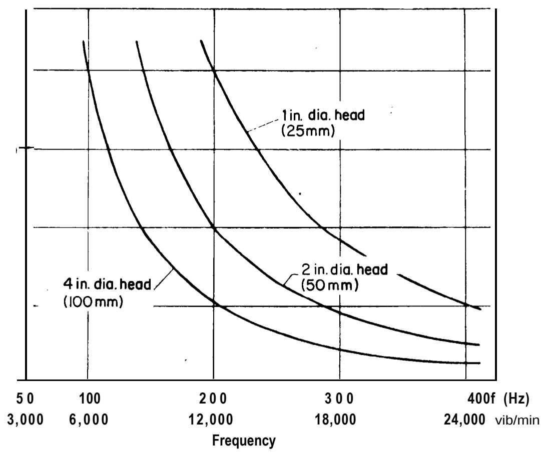


Fig. 3.4.1d-Frequencies and amplitudes not to be exceeded to avoid cavitation

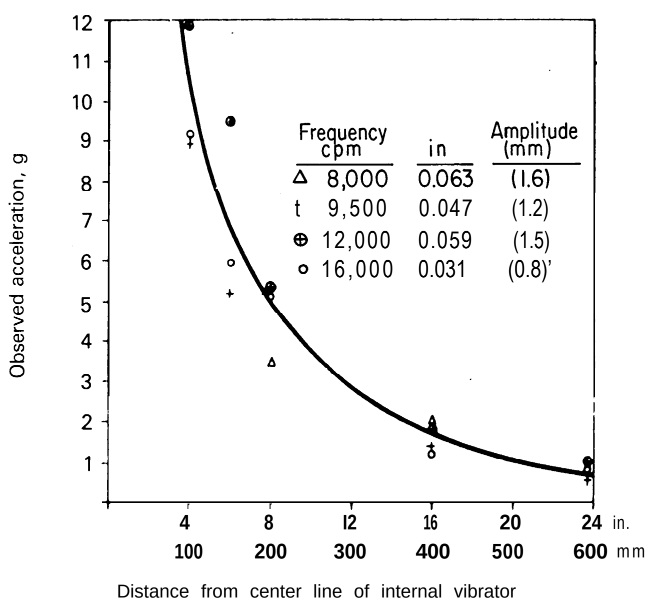


Fig. 3.4.1e-Measured accelerations at different distances from an in tern al vibrator

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 formula, the material damping coefficient of 0.04 represents about 15 percent of total damping, and the geometric energy distribution is 85 percent of the total decrease in amplitude with increasing distance from the vibrator. A damping coefficient of 0.08 correspon-ding to 20 percent of the total damping means that the geo-metric energy distribution dominates. Even if, as indicated by L'Hermite (1948), it is more dependent on frequency than assumed here, the total damping remains essentially inde-pendent of the frequency. (See Fig. 3.4.1e).

A more recent study by Chen et al. (1976) deals with 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.

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 de-aeration 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 com-pared 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. Further studies in this area are desirable.

The radius of action of an internal vibrator is substantially less in reinforced concrete than in nonreinforced concrete. A reduction of 50 percent is not uncommon according to Forssblad (1965).

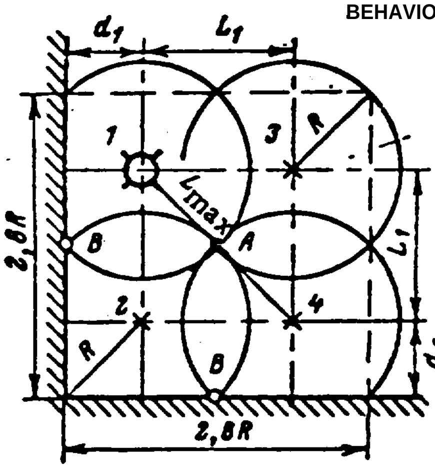
Limiting factors for the transmission of vibrations through fresh concrete have been mentioned. Working in a positive way, however, is the reflection of the compression waves from the form walls which creates standing waves and increased amplitudes in portions of the concrete mass. The resulting radius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

Frame-mounted or gang-mounted internal vibrators are used on concrete paving machines at maximum spacings of about 22 in. (550 mm) at paver speeds up to 18 fpm (5 + 5 m/min) for concrete consistencies of l- to 2-in. (25- to 50-mm) slumps. Overlapping of the compression waves pro-duces an improved consolidation effect when several vibrators are used simultaneously. Frame-mounted internal vibrators have therefore been used at large concrete constructions (Petrov and Safonov 1974). (See Fig. 3.4.lf). To date, however, this method has been used only to a limited extent.

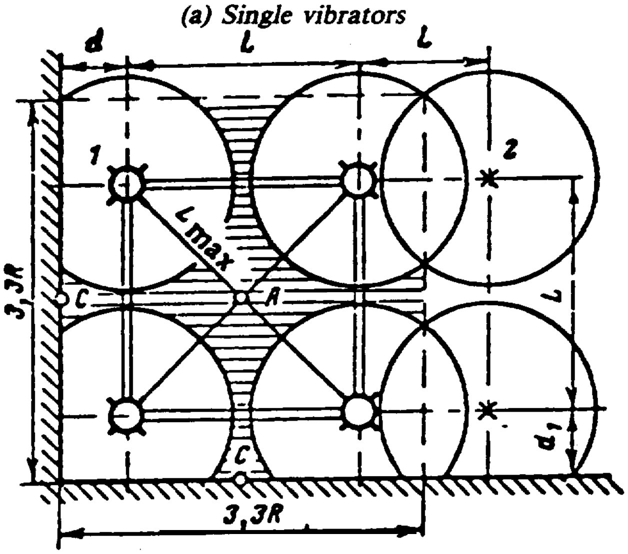
Very stiff mixtures with high coarse-aggregate contents, and low cement contents, such as those used in mass concrete construction, require large-size, heavy-duty internal vibrators. These large-diameter vibrators have lower optimum frequen-cy than regular internal vibrators. In this case, it seems likely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

3.4.2 *Surface vibration*-Surface vibration, illustrated in Fig. 3.4.2, can be accomplished by comparatively light, single, or double vibrating screeds which 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 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 according to Walz (1960)



(a) Single vibrators



(b) Frame-mounted vibrators

Fig. 3.4.1f- Disposition of internal vibrators

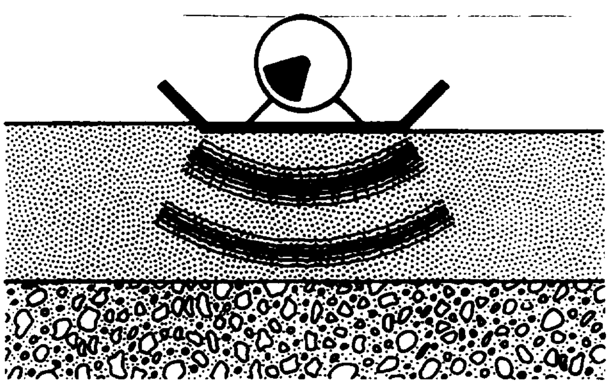


Fig. 3.4.2- Principle of surface vibration

as follows:

$$\text{compaction effort} = \frac{\text{static load x amplitude x frequency}}{\text{rate of travel}}$$

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 represents an interesting new development. Roller-compacted, zero-slump concrete, or rollcrete, has been used in dam constructions and foundations (ACI 207; Cannon 1972; Andriolo, Lobo, and Gama 1984; and Anderson 1983). A properly proportioned mixture is of primary importance. A mixture that is too stiff will not consolidate fully; concrete which 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 discernable 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). However, maneuverability requirements and space limitations 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.

3.4.3 *Form vibration*-In form vibration, it is essential to distribute vibrations uniformly over as large a form surface as possible. (See Fig. 3.4.3a). 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/sec^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/sec^2) (Forssblad 1971).

The amplitude will decrease with increasing distance x from a plane form, according to the following formula. (See Section 3.3.)

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

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

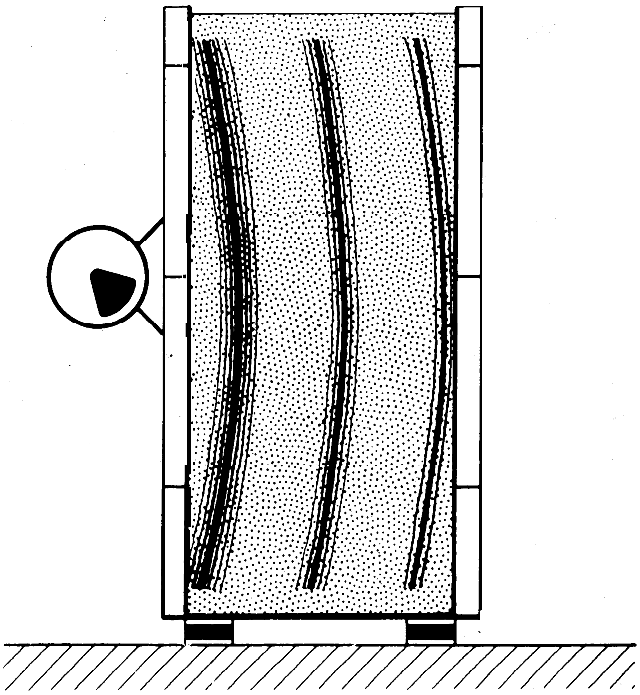


Fig. 3.4.3a-Principle of form vibration

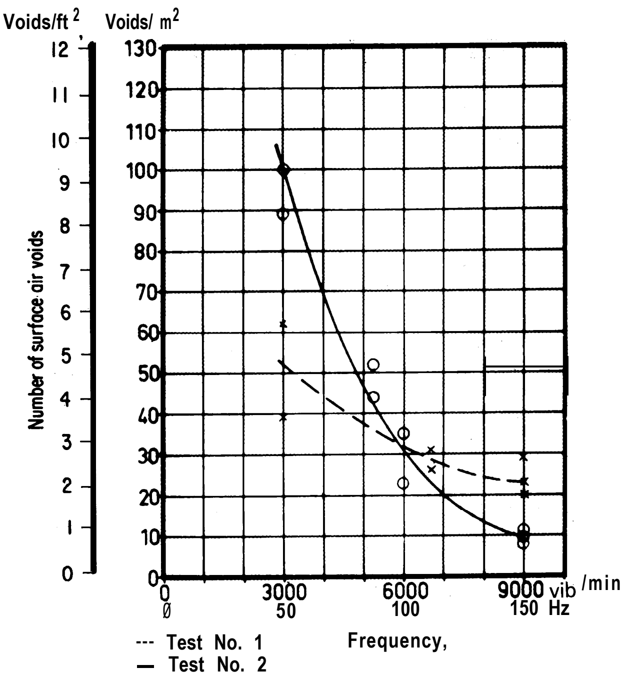


Fig. 3.4.3b-Number of air voids in concrete surfaces obtained by form vibration at different frequencies

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 vibration/min (50 and 200 Hz) are

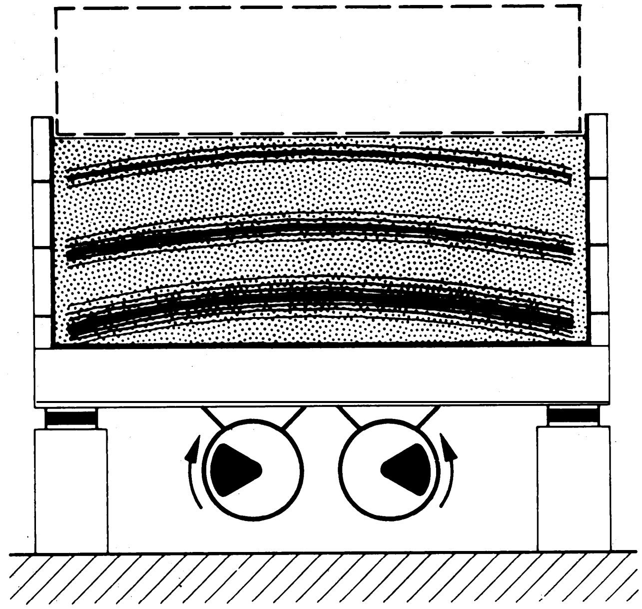


Fig. 3.4.4a-Principle of table vibration

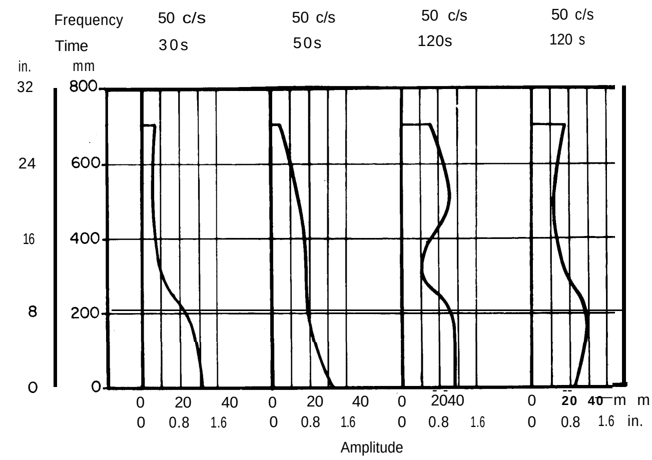


Fig. 3.4.4b-Amplitude distribution in concrete on vibrating table at different frequencies and times of vibration

suitable for form vibration. High frequency form vibration results in a better surface appearance than does form vibration at lower frequency. (See Fig. 3.4.3b). 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.

3.4.4 *Table vibration*-The results of table vibration are often less consistent and more difficult to interpret than results of other vibration processes. (See Fig. 3.4.4a). 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). (See Fig. 3.4.4b.).

The compaction effect is determined by the acceleration of the table. Accelerations of about 5 to' 10 g (49 to 98

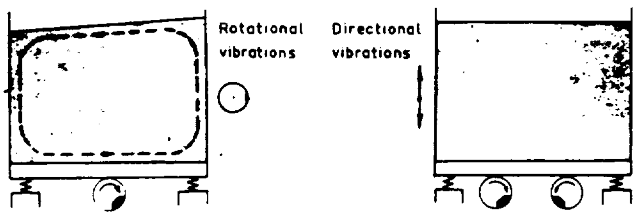


Fig. 3.4.4c-Rotational and directional vibratory motions

m/sec²) before the forms are placed on the table and 2 to 4 *g* (20 to 39 m/sec²) 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 vibration/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 $W = c_1 ms^2 f^3 t$ is also applicable for table vibration, according to Walz (1960). In a stiff fresh concrete, a low vibration intensity can be compensated for by 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 has been 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. With loose forms the vibration time could also be shortened. 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 percent higher concrete strength than did a horizontal circular vibratory motion. A decrease of 10 to 15 percent in strength was obtained with vertically directed vibrations as compared with vertical circular vibrations. (See Fig. 3.4.4c). With fluid to plastic mixtures, these differences are less pronounced. A vertically directed vibratory motion is in many cases preferred, since the movements of the concrete mass are reduced as 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 4-REFERENCES

4.1-Standards documents

The documents of the standards-producing organizations referred to in this document are listed below with their serial designation, including year of adoption or revision. The documents listed were the latest effort at the time this document was revised. Since some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

207.1R-70 (Reapproved 1980)	Mass Concrete for Dams and Other Massive Structures
207.5R-80	Roller Compacted Concrete
211.1-81 (Revised 1984)	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
211.2-81	Standard Practice for Selecting Proportions for Structural Lightweight Concrete
211.3-75 (Revised 1980)	Standard Practice for No-Slump Concrete
309-72 (Revised 1982)	Standard Practice for Consolidation of Concrete

British Standards Institution

BS 1881	Methods of Testing Concrete
1970	Parts 1-5
1971	Part 6

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219

British Standards Institution
2 Park St.
London WlA 2BS
England

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