NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **44**

CONSOLIDATION OF CONCRETE FOR PAVEMENTS, BRIDGE DECKS, AND OVERLAYS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- CEMENT AND CONCRETE
- CONSTRUCTION
- AIR TRANSPORT

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1977

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest and usefulness to construction engineers and others seeking information on concrete consolidation. Detailed information is presented on concrete pavements, bridge decks, and overlays.

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems. Syntheses from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

There has been a surprising scarcity of assembled information on the subject of concrete consolidation. This situation has become more acute due to factors such as new design concepts, changes in equipment and methods of construction, and increased use of deicing agents. This report of the Transportation Research Board describes and evaluates current procedures for consolidation of concrete for pavements, bridge decks, and overlays. Research needs are identified.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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This synthesis was completed by the Transportation Research Board under the supervision of Paul E. Irick, Assistant Director for Special Projects. The Principal Investigators responsible for conduct of the synthesis were Thomas L. Copas and Herbert A. Pennock, Special Projects Engineers.

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William G. Gunderman, Engineer of Materials and Construction, Transportation Research Board, assisted the Special Projects staff and the Topic Panel.

Information on current practice was provided by many highway agencies. Their cooperation and assistance was most helpful.

CONSOLIDATION OF CONCRETE FOR PAVEMENTS, BRIDGE DECKS, AND OVERLAYS

SUMMARY

The benefits of good consolidation of fresh hydraulic-cement concrete include increased strength and abrasion resistance with reduced permeability and a more durable concrete structure. Conversely, significant problems often resulting from improper consolidation are caused by the fact that specifications are neither uniform nor specific in describing the consolidation process and, in some cases, the determination of the adequacy of consolidation is restricted by the experience and judgment of the inspector. Higher placement rates and increased use of reinforcement further enhance the problems of proper consolidation.

Concrete quality and the required consolidation effort both increase as the water content is lowered. However, sufficient water must be present in the mixture to enable concrete to be properly compacted. Admixtures offer some help in reducing compactive effort. Because stiffer mixtures are more difficult to handle and to compact, some concrete unfortunately is placed at or near a self-leveling consistency. The terms used to describe the consolidation characteristics of fresh concrete are consistency, workability, and compactibility.

Internal vibrators are essential for placement of concrete of low water-cement ratio and are widely used for consolidation of pavements and bridge decks. The use of surface vibrators that both strike off and consolidate is increasing for bridge-deck construction. Although consolidation of concrete by mechanical vibration was first accomplished early in this century, it was not until the 1930s that this method became widely used. Later emphasis has been on research and equipment development.

Concrete resists consolidation primarily because of internal friction and interference between aggregate particles. When concrete is properly vibrated, the impulses "liquefy" the mortar portion of the concrete, thus reducing friction and permitting consolidation by gravitational forces. Consolidation by vibration is a two-stage process. The first stage consists of subsidence, a vertical settling of the concrete; during the second stage, entrapped air is removed. The effectiveness of the vibrator is the result of compression waves generated in the concrete. The characteristics of mechanical vibration equipment that define performance are frequency, amplitude, centrifugal force, and radius of action. The relationships among these can be estimated by theoretical considerations involving simple mathematics.

Honeycombing and excessive entrapped air are the major problems associated with undervibration. Although the problems associated with undervibration are more numerous, in some cases overvibration can cause segregation. Most problems ascribed to overvibration, however, result from improper proportioning of the mixture; the desirable solution is adjustment of the mixture rather than reduction of vibration.

In-depth research has identified some of the factors affecting concrete con-

solidation. Among these are slump, mixture proportions, vibrator size, frequency, amplitude, paver speed, vibrator spacing, depth and angle of vibrator, segregation, and air content.

The unit weight of fresh concrete and the specific gravity or density of cores or other specimens are primary indicators of the degree of concrete consolidation. Because of the delay between placement and testing of hardened concrete, there is a need for a rapid and nondestructive method for measuring density and consolidation. Nuclear test methods have been used extensively on an experimental basis for this purpose.

A 1972 survey of practices followed by specifying agencies shows the differences in equipment type, spacing of vibrators, frequency ranges, amplitude requirements, paver speed, and vibrator check procedures. Contractors and equipment manufacturers also provided information that is summarized in this synthesis.

The differences between pavements and bridge decks and the special requirements for bridge-deck concrete placement, vibration, and finishing are reviewed herein. Revibration to increase consolidation is also discussed.

Surface vibrators usually are required for thin overlays over either pavements or bridge decks. Special techniques have been developed for consolidation of extra-thin overlays, including specific equipment requirements and prompt vibration.

The following conclusions are offered:

- Consolidation by vibration improves all of the important properties of concrete in pavement, bridge deck, and overlay slabs.
- The consolidation achieved by vibration is a function of vibrator characteristics as well as the consistency and workability of the concrete mixture.
- Internal vibration appears to be the most effective means of concrete consolidation for pavements and bridge decks.
- There appear to be fairly large ranges within which vibrator frequency, eccentric size, and time of insertion can vary without substantially affecting the degree of consolidation achieved.
- Continuous monitoring of vibrators is required at all times to ensure proper operation.
- A minimum head or surcharge of 4 to 6 in. (100 to 150 mm) of concrete over an internal vibrator is recommended.
- The most commonly specified minimum frequencies for conventional paving concrete are 7,000 vpm for internal (spud) vibration, 5,000 vpm for tube vibration, and 3,500 vpm for surface vibration. These values are slightly lower than those recommended by the American Concrete Institute (ACI).
- Vibrator frequencies for bridge-deck concrete are not defined satisfactorily in most specifications.
- Problems with undervibration are more widespread and serious than any problem of overvibration.

Areas identified that could benefit from additional research or study are materials, equipment, construction practices, specifications, and education of project personnel.

CHAPTER ONE

INTRODUCTION TO CONCRETE CONSOLIDATION

PURPOSE OF CONSOLIDATION

Consolidation is defined in this report as a purposeful action taken to reduce a freshly placed hydraulic-cement concrete mixture to the minimum practical volume through the elimination of all voids except those intentionally included to improve durability (entrained air). All of the important properties of concrete are improved by proper consolidation. Permeability is reduced, and strength and abrasion resistance are increased. Resistance to freezing and thawing and to attack by aggressive fluids is also increased. Within reinforced concrete, bond to reinforcement is improved and penetration of deicing chemicals is retarded. Conversely, strength and durability are reduced by improper consolidation; in addition, performance and appearance are adversely affected by large, uncontrolled voids.

Although the production of strong and durable concrete involves a number of interrelated factors, consolidation is certainly one of the most vital. Despite the obvious importance of consolidation to concrete performance, a surprising number of specifications state merely that the concrete shall be adequately consolidated. In some cases admonitions against overvibration are included.

Over the past forty years many of the factors influencing proper consolidation have been identified; however, translation of this research into practice has been complicated by the fact that the consolidation process is a qualitative one requiring experience and judgment. The compactive effort necessary to achieve proper consolidation depends on the properties of the concrete mixture being compacted, the characteristics of the equipment, the method used, and the geometry and congestion of reinforcing steel within the spaces into which the concrete must be placed.

Increased emphasis has been placed on mechanical equipment that permits placement of pavements and bridge slabs at a rapid pace. In addition, current design concepts for some pavements and most bridge slabs encourage increased use of reinforcing steel. Both trends increase congestion and complicate the consolidation process.

Proper consolidation requires matching of the concrete mixture, mechanical equipment, and consolidation procedures. This synthesis focuses on recent research and field practice on consolidation of hydraulic-cement concrete for pavements and bridge slabs. Full-depth and overlay construction are also included. The synthesis also examines (a) parameters affecting consolidation, (b) methods of consolidation, (c) construction practices, and (d) current specifications. The questions of the adequacy of consolidation and methods by which consolidation can be measured are also addressed.

GENERAL ASPECTS OF CONSOLIDATION

An examination of the general relationship between concrete quality and water content provides considerable insight into the significance of consolidation. Figure 1 illustrates this relationship. As may be seen from this figure, concrete quality decreases as water content increases. This holds true regardless of the particular property used to characterize quality, provided the mix materials, curing conditions, and degree of consolidation are held constant. However, as the water content is reduced, the concrete becomes more difficult to compact and at some point the consolidation that can be achieved with a given compactive effort is also reduced. This, in turn, reduces the quality of the concrete as illustrated by curves A through D in Figure 1.

Most concrete placed in transportation facilities would probably fall into the C designation, with consistencies ranging from very stiff to stiff plastic. Concrete of these consistencies must be consolidated by vibration with mechanical equipment. A few transportation applications may require extremely stiff or zero-slump concrete. Some concrete unfortunately is placed in transportation facilities with near-flowing or self-leveling consistency. Although this type of concrete requires little or no compactive effort, this easy approach to consolidation is achieved at the expense of premature deterioration.

The curves shown in Figure 1 also illustrate that consolidation does not remove all entrapped air, particularly in stiffer mixtures. For a given consistency level and concrete mixture there is an optimum combination of water content and compactive effort that results in the greatest improvement of concrete quality. If the concrete is too dry for the compactive effort being provided, quality decreases. If the consistency of the concrete is changed by the addition of water, the concrete is densified by more ready removal of entrapped air, but the quality is compromised by the detrimental influence of the added water (*1*). Despite the generally detrimental effects of added water, concrete must be sufficiently workable to be properly consolidated. This is often accomplished without the addition of water by increasing the sand content; however, this tends to increase the cost of the mixture. Excess workability derived by increasing the water content decreases the quality of the concrete (*1*).

Admixtures can improve the workability and compactability of concrete, particularly in heavily reinforced sections; they also usually improve durability. Air entrainment, which is used to improve durability, offers the additional benefits of some water reduction, improved cohesiveness, and reduced segregation. Water-reducing admixtures, which usually provide set retardation, also provide improved workability. Although such admixtures delay the setting

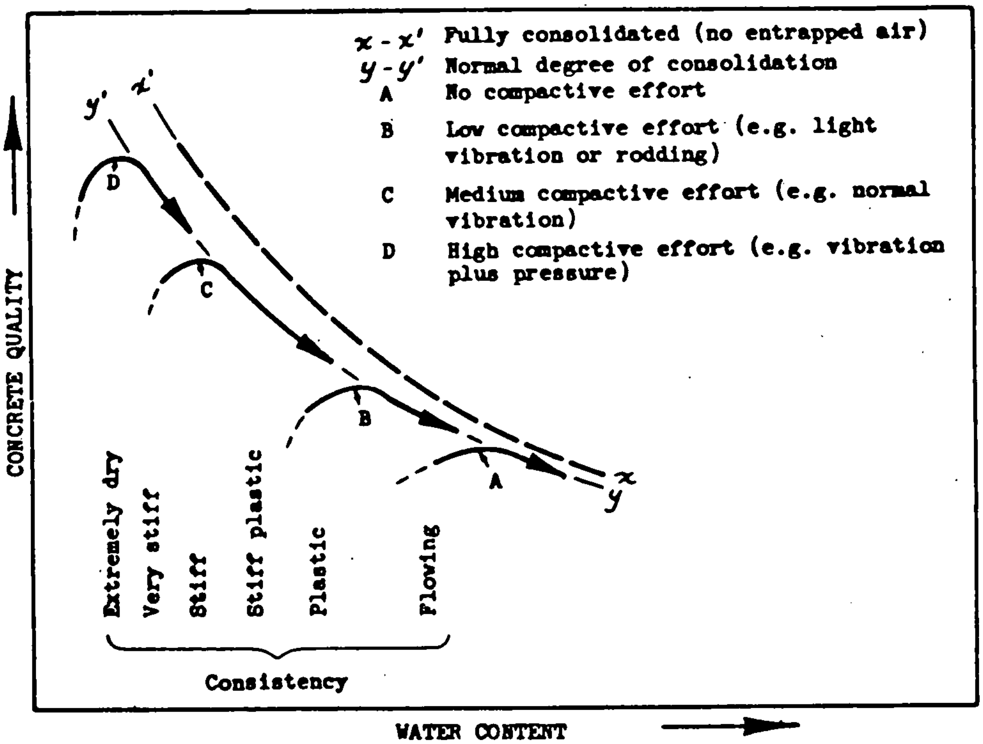


Figure 1. Effect of compactive effort on concrete quality (1).

of concrete as measured by penetration resistance, data indicate that loss of slump with time is often increased. Even though increased slump loss adversely affects compaction, admixtures permit the use of higher slump concretes of low water-cement ratio and thus are useful particularly in heavily reinforced sections.

Mixtures having a moderately high slump, small maximum size of aggregate, and excess sand are often popular with field personnel because the excess workability means less work in placing. At the other extreme, it is inadvisable to use mixtures that are too stiff for the placing conditions. These mixtures require great compactive effort and may be incapable of being properly consolidated.

TABLE 1

CONSISTENCY RANGES

Consistency Description	Slump, Inches (cm)	Vebe Time, Seconds
Extremely Dry	-	32 to 18
Very Stiff	-	18 to 10
Stiff	0 to 1* (0 - 2.5)	10 to 5
Stiff Plastic	1 to 2 (2.5 - 5)	5 to 3
Plastic	3 to 4 (8 - 10)	3 to 0*
Flowing	5 to 7 (13 - 18)	-

* Test method is of limited value in this range.

Several terms are used, sometimes interchangeably, to describe the characteristics of concrete that affect consolidation. These include consistency, workability, and compactibility.

Consistency

Consistency is the ability (or inability) of concrete to flow; thus, it is closely related to the response of concrete to consolidation. Pavement slabs usually require concrete of stiff plastic consistency, whereas structural slabs are normally constructed of wetter concrete with a less stiff consistency.

Consistency is basically wetness and is conventionally estimated in the field by simple test methods such as slump (ASTM C 143, AASHTO T 119) or ball penetration (ASTM C 360, AASHTO T 183).

In the laboratory, flow tables are often used. The Vebe test, which uses a combination of a remolding apparatus and vibrating table, seems to be most suitable for measuring the consistency of stiff and very stiff concrete; it is not used in the United States, however. ACI Committee 211 (2) has classified concretes over the entire range of consistency according to the values for slump and Vebe time as given in Table 1.

Workability

Workability is a more general and less measurable property that relates to the ease of handling, finishing, and consolidating. The major distinction between workability and consistency is that workability includes such traits as flowability, moldability, cohesiveness, and compactibility. Workability is affected by grading, particle shape, and proportions of the aggregate; cement content; admixtures, if used; and consistency of the mixture. Once the materials and mixture proportions are fixed, workability is controlled by changing the consistency which, in turn, is controlled by changing the water content. As previously discussed, however, increased water content leads to reduced durability and strength.

Compactibility

Compactibility is sometimes used to describe the response of the concrete to consolidation through overcoming of internal friction within the concrete, or between the concrete and its boundary surfaces, forms, or reinforcement. Compactibility is affected by grading, particle shape, and proportions of the aggregate; cement content; admixtures, if used; and consistency of the mixture. (This definition is somewhat different from that used when discussing soils.)

CONSOLIDATION EQUIPMENT

Some consolidation is derived by the action of gravity on the concrete as it is deposited in the form or on the grade. Foot tramping, rodding, spading, and various forms of manual manipulation also provide consolidation, particularly if the concrete is wetter than may be desirable.

The consolidation process most widely used for stiffer mixtures is vibration by any of several mechanical methods. Mechanical vibration is especially adaptable to the stiffer consistencies used in construction of transportation facilities. Concrete vibrators provide a rapid oscillatory motion that is transmitted to the fresh concrete. Such oscillating motion is basically described in terms of frequency (number of oscillations or cycles per unit of time) and amplitude (deviation or maximum movement from point of rest).

Vibrators may be of either internal or external type. When internal vibrators are immersed in concrete, the vibratory waves are transmitted perpendicular to the long axis of the vibrator. When external vibrators are applied to surfaces, vibratory waves penetrate into the concrete.

Vibrating tables, tamping bars, form vibrators, and equipment for centrifugation (spinning) are not applicable to the consolidation of slabs and thus are not covered in this synthesis.

Internal Vibrators

The most widely used and most important type of consolidation for pavement and bridge slabs is internal vibration. Internal vibrators, often called spud or poker vibrators, have a vibrating casing or head that is immersed directly in the concrete. In most cases internal vibrators depend on the cooling effect of the surrounding concrete to prevent overheating. An internal vibrator acting on low-slump concrete is shown in Figure 2.

Most, if not all, internal vibrators marketed in the United States are classified as rotary vibrators. As the eccentric or unbalanced weight rotates about the axis, it causes the vibrator to revolve in a circular path or revolution. Each complete revolution is a vibration or vibratory cycle. During the rotation, vibrations, accelerations, and centrifugal forces are created that are imparted to the concrete at right angles to the axis of the vibrator. (The processes of consolidation and important mathematical relationships are discussed later in this synthesis.)

Internal vibrators may be hand held and used individually (as in bridge-deck construction) or they may be gang mounted (as in paving). Most hand-held internal vibrators are of the flexible-shaft type with the electric or gasoline motor outside the vibrating head. In some cases air-turbine motors are used to turn the shaft. A flexible shaft leads from the motor to the head, where it turns an eccentric weight.

Motor-in-head vibrators have the motor located in the head and are generally larger than the flexible-shaft type. They are widely used on large jobs and on most paving equipment. In the general construction industry, in-head types are increasing in popularity. The motor may be electric or hydraulic; although most are now electric, use of hydraulic motors is increasing. An electric motor-in-head vibrator is shown in Figure 3.

A typical paver with gang-mounted internal vibrators is shown in Figure 4.

In the past, a tube vibrator immersed in the concrete at right angles to the direction of paver travel was used for vibration. The vibrating tube operates in a manner similar to that of the spud vibrator. Even though use of the tube vibrator has declined, some pavers are equipped with spud vibrators mounted at right angles to the direction of paver travel, approximating the action of a tube vibrator. This technique may be especially useful where reinforcing steel is not used.

External Vibrators

Three types of surface vibrators are used in concrete pavement and bridge slab construction: pan vibrators, vibratory screeds, and vibratory roller screeds. The pan type is used strictly for consolidation. The other two are dual-purpose units that both strike off and provide some consolidation of the slab. They are used increasingly in bridge-deck construction. A pan vibrator is shown in Figure 5, a vibratory screed in Figure 6, and a roller finisher for bridge-deck construction in Figure 7.

In addition to mechanical vibration applied externally to the surface, special processes have been used experimentally for small slabs. Recently there has been renewed interest in vacuum dewatering, a process by which a vacuum is applied over the surface of the slab (*3*). This process brings excess water to the surface more rapidly than would be the case under the action of gravity alone. Removal of this water permits earlier finishing, particularly of floor slabs and precast units. Consolidation and densification of the concrete mass are associated with the removal of water.

HISTORICAL DEVELOPMENT OF VIBRATION FOR CONSOLIDATION

The benefits of dry mixtures of mortar subjected to intense compaction have long been realized. The Romans produced durable structures by ramming dry ingredients into

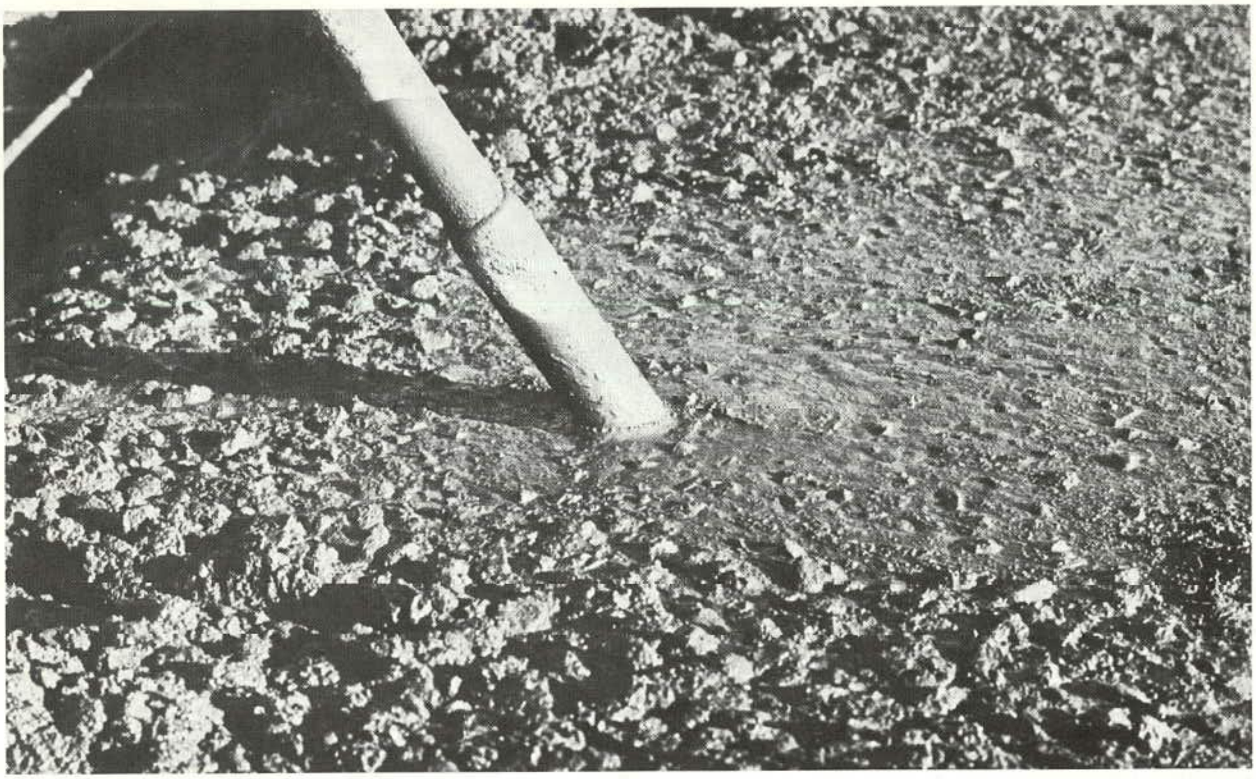


Figure 2. Internal vibrator "liquefying" low-slump concrete (1).

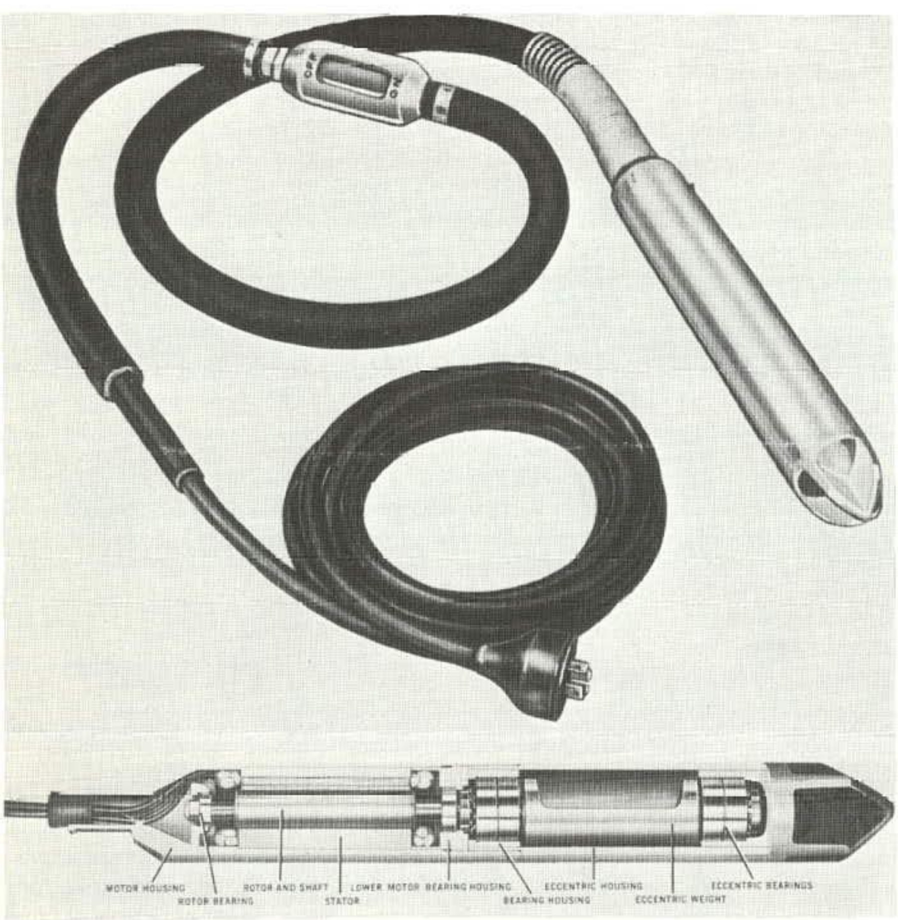


Figure 3. Electric motor-in-head vibrator; external appearance (top) and internal construction of head (bottom).

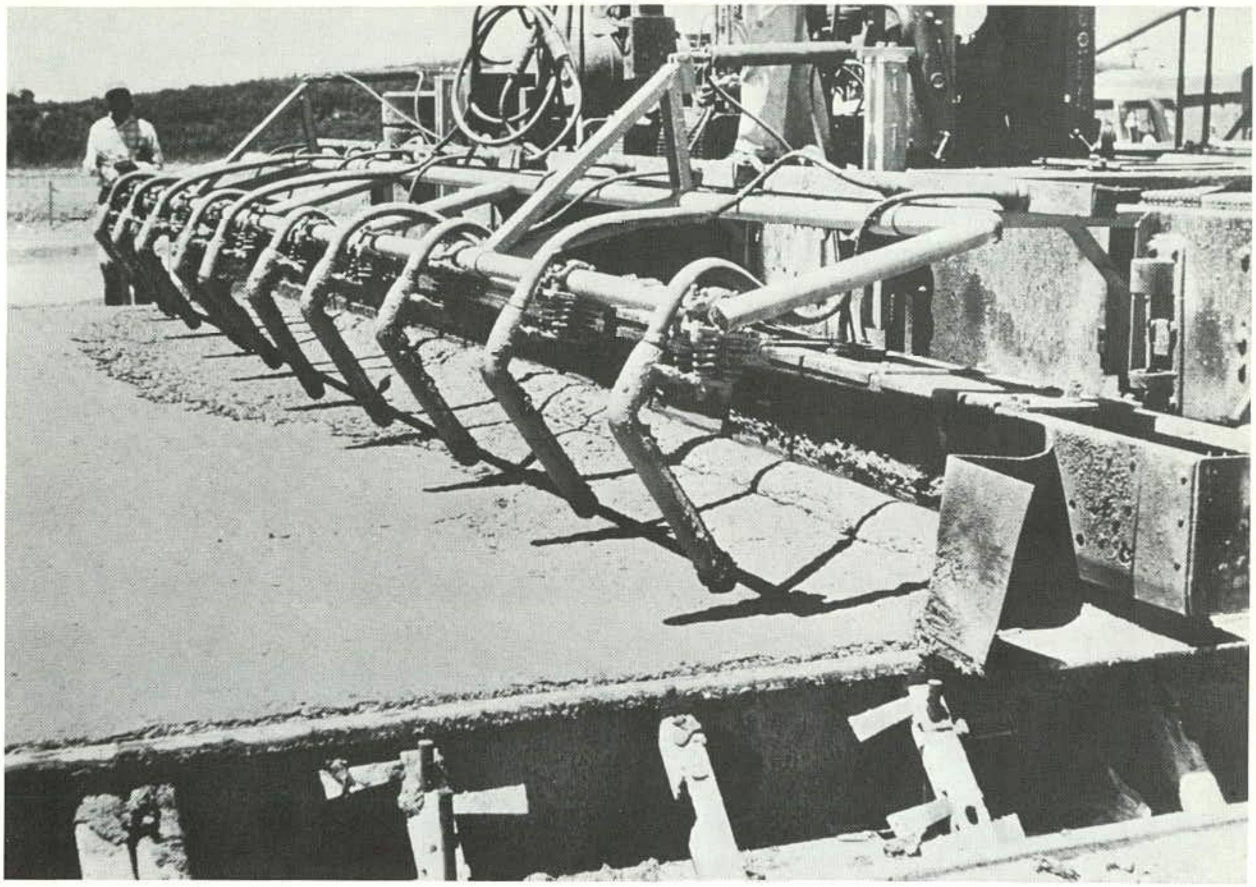


Figure 4. Gang-mounted spud vibrators (in the withdrawn position) for consolidating concrete pavement (1).

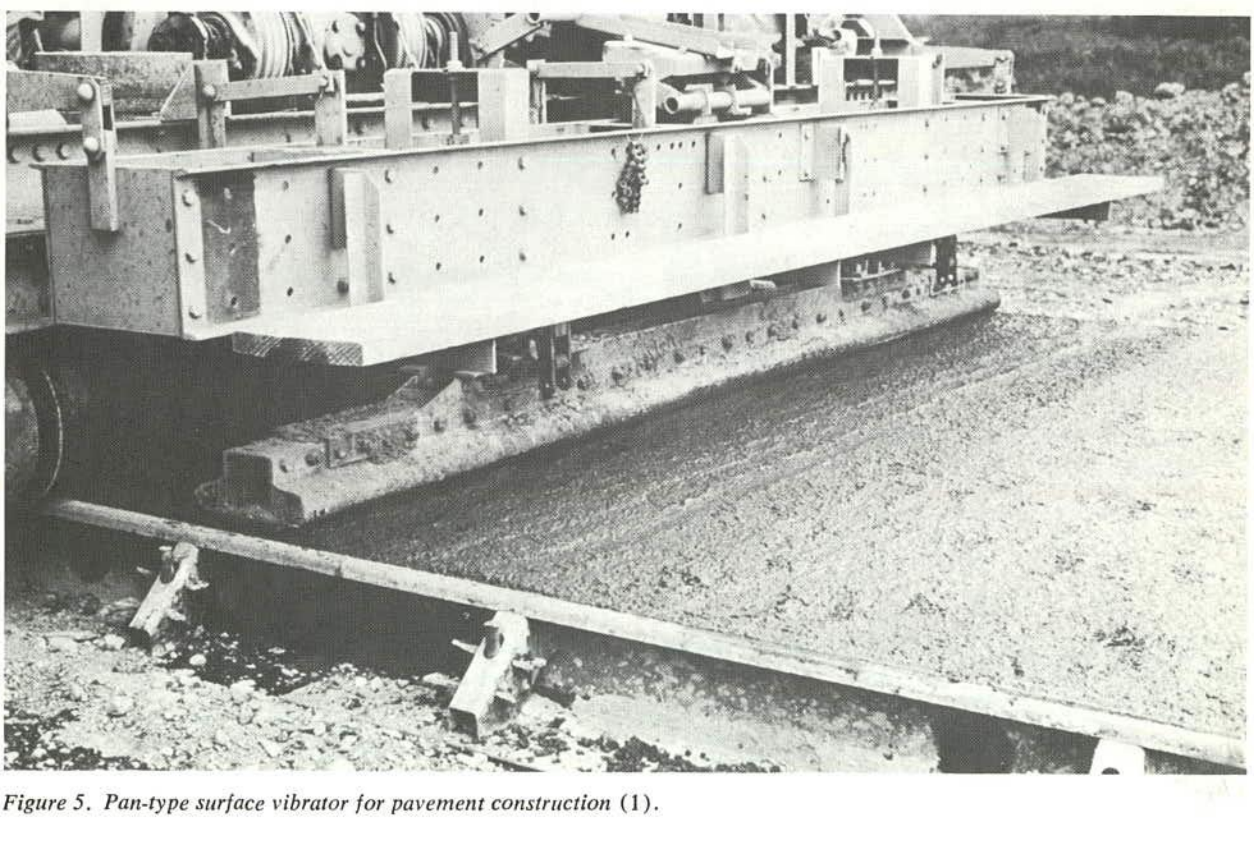


Figure 5. Pan-type surface vibrator for pavement construction (1).

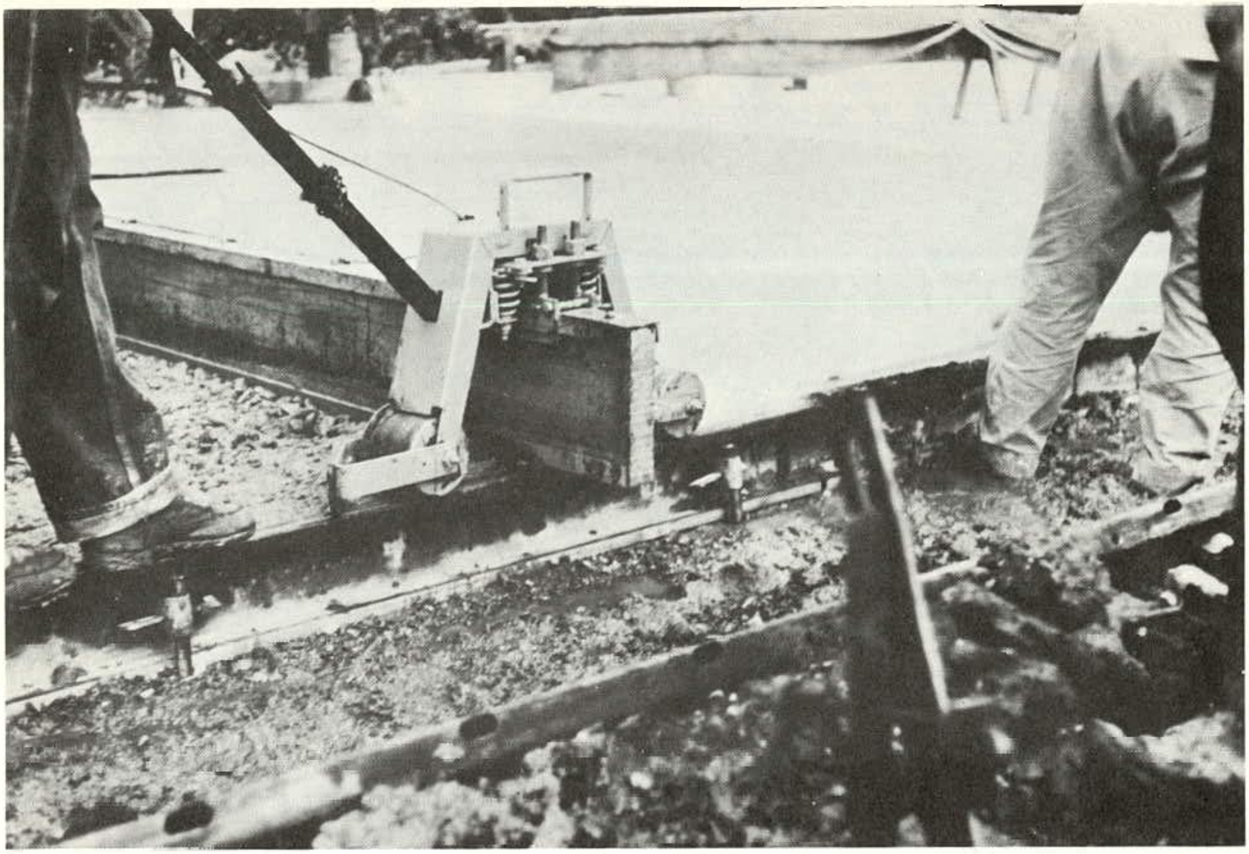


Figure 6. Vibratory screed for pavement construction (1).

place and then adding only the amount of water necessary for hydration. In the United States during the 19th century, the emphasis was largely on flowable grouts and mortars, but even then the need for stiff, well-compacted mixtures was recognized (*4*).

Early in the 20th century, consolidation by mechanical vibration was developed. Tables with "jiggers" were used for molding concrete pieces (*5*). In Europe, pavements were first consolidated mechanically in 1911; before 1920, air percussion hammers were applied as form vibrators (*6*). In 1919, Abrams (*5*) reported experiments on vibration, jigging, and pressure on concrete. Although he used no internal vibration, Abrams concluded "that with jigging high strength may be secured with drier mixes than would be feasible otherwise." Immersion vibrators appeared in the 1920s, but were not fully developed until the early 1930s when mechanical vibration of concrete was used first for shipbuilding and later for pavements and bridges and particularly in the construction of dams. In 1933, McCarty (*7*) reported on a seven-year study that included a practical approach to improved placing methods. This report described five different vibrators. During the same period, studies from the Bureau of Public Roads (*8*) and Missouri (*9*) described several different types of paving machines featuring vibration, which were essentially surface vibrators. In 1933, Michigan reported its experience with three types of vibrators used on large-scale work (*10*). In 1934, favorable reports on pavement vibration based on several years of experience were issued by New Jersey (*11, 12*), Illinois (*13, 14*), Michigan (*15*), and Ohio (*16*). New Jersey's 1934 report described experience with a variety of structures. In 1935, Hathaway (*17*) reported that Illinois now required internal vibration for bridge construction.

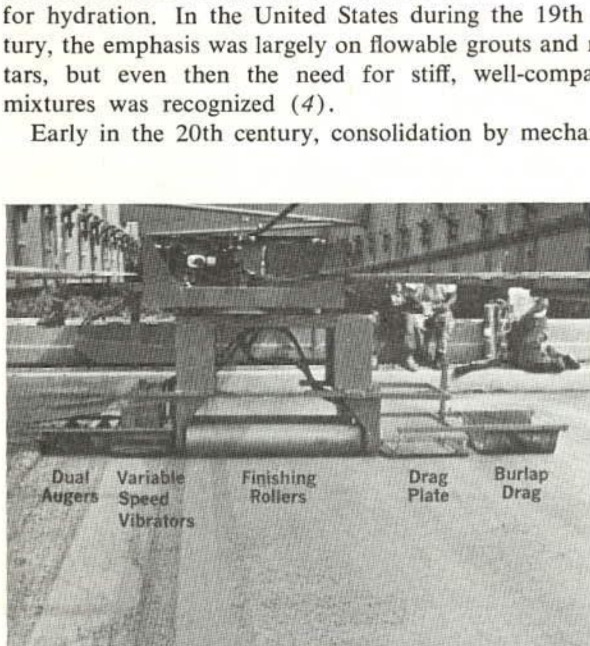


Figure 7. A roller finisher for bridge deck construction (CMI).

In 1935, a suggested specification for vibrated concrete in pavements based on work by the Bureau of Public Roads and several states was published (*18*). This specification included a maximum water-cement ratio but also contained a provision that the proportions be adjusted to give approximately a 1-in. (25-mm) slump. The minimum quantity of sand necessary to give the required workability was suggested. According to the specification, plasticity under vibration was the critical measure of workability rather than plasticity of the freshly mixed concrete.

In 1936, ACI Committee 609 issued its first report (*19*), which dealt largely with form vibrators, but recommended that internal vibrators be used for all elements sufficiently large for internal insertion and manipulation.

Since the 1930s, the emphasis has been on research and equipment development to refine the benefits of mechanical vibration recognized earlier. Many current specifications still reflect the concepts developed during that earlier period.

After the initial introduction of vibration, better equipment and more responsive mixtures were developed. With the advent of air entrainment in the mid-1940s, attention was directed toward studies of the vibration of air-entrained concrete. By the mid-1940s the applicability of vibration to concrete pavements and structures had been proven. Numerous general research efforts continued on vibration, vibration of precast products, and attempts to explain quantitatively the response of concrete to vibration. In the United States, comparatively few field studies have been reported since World War II; however, in England, Europe, and Scandinavia, extensive post-war research has been conducted. The more notable efforts include works of the Road Research Laboratory (*20*), Forssblad of Sweden (*21*), Dutron of France (*22*), and Garbotz et al. of West Germany (*6*). Unfortunately much of this excellent work has not been translated and much that has been is buried in relatively obscure research journals. Summaries are available, however [for example, see Ref. (*82*)].

In the late 1960s, interest in consolidation was renewed as increased emphasis was placed on high-volume production, increased use of slip-form equipment for paving, and development of specialized mechanical equipment for bridge-deck construction. This research is summarized in Chapter Four.

CHAPTER TWO

THEORETICAL ASPECTS OF CONSOLIDATION BY VIBRATION

Although this synthesis is directed principally toward field practices, an understanding of several theoretical concepts and parameters used to define the performance of mechanical equipment for either purchasing or specification purposes is important. The parameters of interest are frequency, amplitude, centrifugal force, and radius of action (the distance of effective consolidation from the source). The relationships among them can be developed from theoretical considerations with simple mathematics and can provide a qualitative understanding of the response of concrete to the forces developed by the vibrator.

RESPONSE OF CONCRETE TO VIBRATION

An unconsolidated concrete mass consists of separate mortar-coated aggregate particles. Concrete resists consolidation because of internal friction and interference, particularly among particles. The larger particles support an arching action, which, along with various surface tensions and cohesive forces within the concrete mass, results in large quantities of air-filled space. The amount of this entrapped air depends on a variety of factors; the amount is usually between 5 and 20 percent by volume (*1, 23-25*). The amount of entrapped air in very dry mixtures can be as much as 30 percent by volume (*24*).

When a concrete mass containing these voids is subjected to proper vibration, the rapid vibratory impulses "liquefy" the mortar portion of the concrete (i.e., reduce the internal friction, which, in turn, permits consolidation of the mass by gravitational forces).

Consolidation by vibration is a two-stage process. The initial stage comprises the major subsidence, or "slumping," of the concrete. This subsidence is essentially a vertical settling. During this stage the mixture becomes unstable and the solids, particularly the coarse-aggregate particles, seek a lower position, thus densifying the mass (*1*). Popovics (*23*) has suggested that the shape of the coarse-aggregate particles is of decisive importance. The first stage of consolidation is completed when the overwhelming majority of the coarse-aggregate particles stop moving downward.

After the initial stage of consolidation, honeycombing is essentially eliminated and the large voids among the coarse-aggregate particles are filled with mortar. The mortar still contains numerous entrapped air bubbles as large as approximately 1 in. (25 mm) and amounting to several percent by volume of the concrete (*1*).

In the second stage of consolidation, the mortar (or, in particular, the cement paste) assumes the major role transmitting pressure waves more efficiently. This causes the entrapped air voids to rise to the surface and escape. Because of their greater buoyancy, larger bubbles are more easily removed than smaller ones. Air voids near the vibrator are released before those near the fringes of the radius of action. There is also some indication that vibration itself creates small bubbles, probably by dividing larger ones (*26*). The removal of voids (i.e., consolidation) is a continuous process, rapid at first and then diminishing. It is possible, however, given the proper vibrator, concrete mixture, and amount of time, to remove most entrapped and, to a lesser extent, entrained voids.

In air-entrained concrete, which is essentially all concrete used in transportation facilities, from 4 to 9 percent of the concrete by volume is occupied by purposefully entrained voids predominantly less than 0.03 in. (0.75 mm) across. In air-entrained concrete the goal of proper consolidation is to remove the vast majority of the larger entrapped voids and the largest of the entrained voids. Removing all of the entrapped air with a conventional vibrator would take an unreasonably long vibrating time. Therefore, it is considered normal to have as much as 1 percent of large entrapped voids in properly consolidated concrete.

The effectiveness of a vibrator is due to the compression waves that it generates in the concrete. These waves move the water molecules more than they do the solid particles of cement and aggregate (*27*). This action, which amounts to a back and forth flow of water between the particles, generates hydraulic pressures that are highest where the restriction of flow is greatest; namely, the points of contact between particles. In consequence, this pressure increases the minimum distance between particles at the expense of the wider distances, resulting in a greatly reduced internal friction that imparts temporary fluidity to the paste. In a similar manner, the pressure waves in a concrete mass move the cement paste more than they do the larger aggregate particles, resulting again in a reduced friction between aggregate particles (*27*).

Waves passing through concrete are rapidly attenuated or reduced with distance from the source because of the expanding area of the wave front and the absorption of energy (damping) by the concrete (*28*). Thus, waves are effective for only a relatively short distance. A number of factors influence attenuation, such as the presence of entrained air and the characteristics of vibration, including frequency. There is evidence that attenuation or reduction of radius of action increases with frequency (*28*). This may impose an upper limit to usable frequencies because the increase in power input with frequency will be offset by the increase in attenuation.

In the broadest sense, consolidation by surface vibration occurs by the same mechanism as that of internal vibration. Compression waves are generated and accelerations are imparted that cause downward movements of aggregate particles and other solids. Accompanying the downward movement of the heavier particles is the upward displacement of the lighter solid particles and water. Extensive studies of surface vibration conducted by the Road Research Laboratory are discussed later in this synthesis. Based on these studies, Kirkham and White (*20*) concluded that the main factors influencing consolidation from the surface are "the amplitude of vibration, the number of vibrations transmitted to the concrete, and the force exerted on the concrete." These are the same factors that influence compaction by internal vibration; however, the direction of surface vibration is downward, whereas the direction of internal vibration is perpendicular to the axis of the vibrator.

Consolidation is a function of the concrete mixture, the vibrator, and the operation of the vibrator. The goal is for all three of these components to be properly matched.

Mathematical Relationships

When a weight (w) rotates at a constant rate about an axis, the location (M) of any point on the weight with respect to the axis at any time (T) is graphically represented by the simple sine curve as shown in Figure 8.

The maximum amplitude (a) is equal to the radius (r). A complete cycle is traced by one complete revolution of M, during which two impulses of amplitude (a) are imparted to the concrete. Using the well-known mathematical relationships of simple harmonic motion, the maximum acceleration is given by $a\omega^2$ where ω is the angular velocity in radians per second. From the relationships of simple harmonic motion, it is equal to $2\pi n$ where n is the frequency in revolutions per second. Thus, the maximum acceleration (A) is

$$A = (2\pi n)^2 a = \text{maximum acceleration, in./sec}^2 \text{ (mm/sec}^2\text{)} \quad (1)$$

From this equation the acceleration is seen to be proportional to the amplitude and the square of the frequency.

Using the relationship that force (F) is the product of mass and acceleration, and since the mass of the eccentric is its weight (w) divided by the acceleration of gravity (g), then

$$F = \frac{w}{g} 4\pi^2 n^2 r = \text{centrifugal force, lb (N)} \quad (2)$$

The product wr is defined as the eccentric moment of the vibrator.

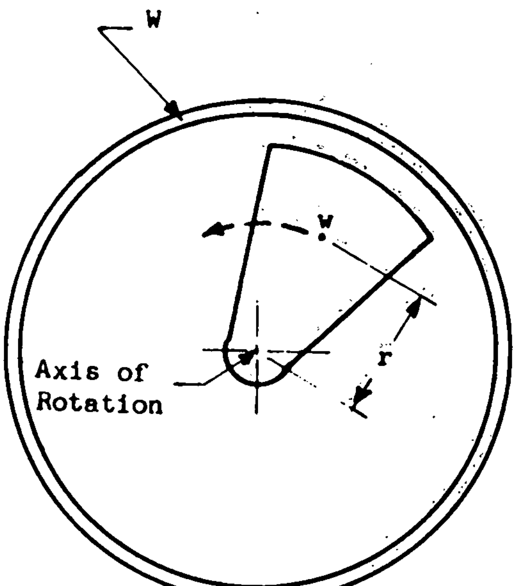
This type of academic calculation has been criticized as encouraging misconceptions because only a portion of the calculated force is transmitted to the concrete (*29*). For vibrators other than the rotary type, the principles of harmonic motion do not apply. Despite the criticisms and lack of general applicability, the basic concepts and mathematical relationships illustrated are useful for visualizing and defining the basic principles of vibration and vibrator characteristics.

PATTERNS OF CONSOLIDATION

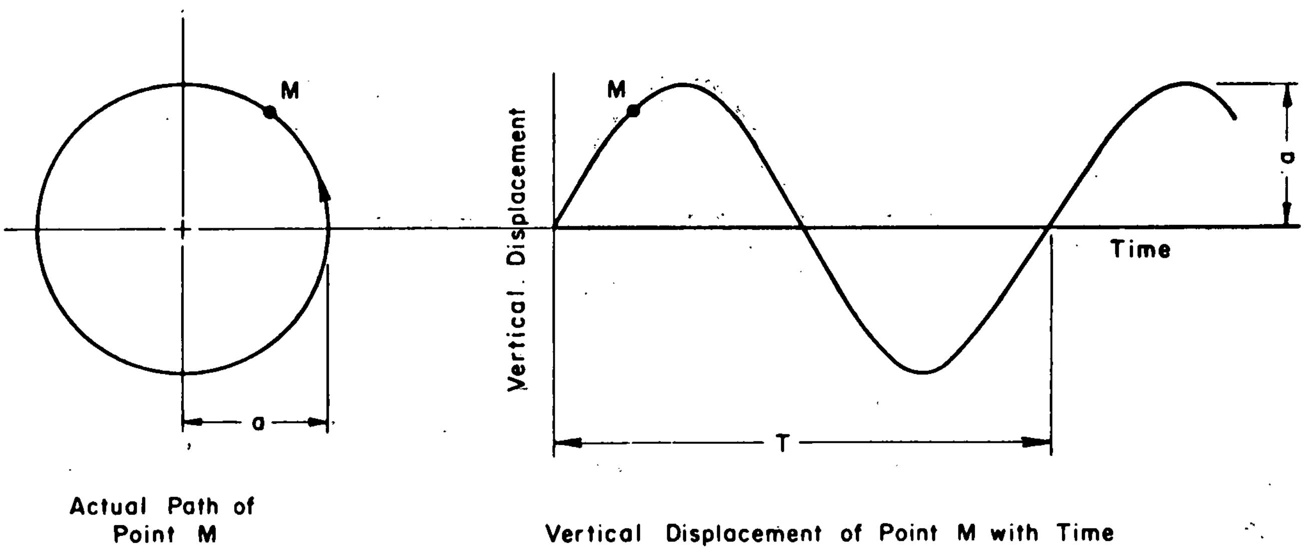
Photographs and descriptions of various types of vibrators are presented in the ACI "Recommended Practice for Consolidation of Concrete" (*1*); detailed specifications are available from the literature of various companies. ACI Committee 309 has classified internal vibrators according to the characteristics given in Table 2.

Vibrators in Group 2 are typical of those used in bridge-deck slabs; in Group 3, they are typical of those used on most mechanical paving equipment. Of particular practical importance are the radii of action and recommended rates of placement for single hand-held vibrators. The maximum radius of action for Group 3 vibrators, as given in Table 2, is 14 in. (350 mm); this distance is important in determining vibrator spacing. It should be noted that the recommended frequencies in Table 2 are values determined when the vibrator is operating in concrete rather than in air.

For proper consolidation a hand-held vibrator should be rapidly inserted as nearly vertical as possible into the concrete and held stationary for 5 to 15 sec until the consolidation is considered adequate. The vibrator should then be withdrawn slowly, at the rate of about 3 in. (75 mm) per sec. The concrete should move back into the hole;



W = weight of shell and other non-moving parts, lb (kg)
w = weight of eccentric, lb (kg)
$W + w$ = total weight of vibrator
r = eccentricity, i.e., distance from center of gravity of eccentric to its center of rotation, in. (cm)



M = random point on vibrator spud

T = time for one complete revolution or vibration cycle, sec

$n = 1/T$ = frequency, vibration cycles or vibrations per sec (Hz)

a = amplitude (deviation from point of rest),* in. (cm)

$A = 4\pi^2 n^2 a$ = acceleration, in. per sec² (cm/sec²)

Acceleration, g's, $= \frac{4\pi^2 n^2 a}{g}$, where g is 386 in. per sec² (981 cm/sec²)

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

Figure 8. Geometric relationships (1).

TABLE 2

RANGE OF CHARACTERISTICS, PERFORMANCE, AND APPLICATIONS OF INTERNAL VIBRATORS (*1*)

Column (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
			Suggested values of			Approximate values of		
Group	Diameter of head, in. (cm)	Recommended frequency, vibrations per min (Hz)	Eccentric moment, in.-lb (cm-kg)	Average amplitude, in. (cm)	Centri-fugal force, lb (kgf)	Radius of action, in. (cm)	Rate of concrete placement, cu yd per hr per vibrator (m^3/hr)	Application
1	¾-1½ (2-4)	10000-15000 (170-250)	0.03-0.10 (0.035-0.12)	0.015-0.03 (0.04-0.08)	100-400 (45-180)	3-6 (8-15)	1-5 (0.8-4)	Plastic and flowing concrete in very thin members and confined places. May be used to supplement larger vibrators, especially in prestressed work where cables and ducts cause congestion in forms. Also used for fabricating laboratory test specimens.
2	1¼-2½ (3-6)	9000-13500 (150-225)	0.08-0.25 (0.09-0.29)	0.02-0.04 (0.05-0.10)	300-900 (140-400)	5-10 (13-25)	3-10 (2.3-8)	Plastic concrete in thin walls, columns, beams, precast piles, thin slabs, and along construction joints. May be used to supplement larger vibrators in confined areas.
3	2-3½ (5-9)	8000-12000 (130-200)	0.20-0.70 (0.23-0.81)	0.025-0.05 (0.06-0.13)	700-2000 (320-900)	7-14 (18-36)	6-20 (4.6-15)	Stiff plastic concrete [less than 3-in. (8 cm) slump] in general construction such as walls, columns, beams, prestressed piles, and heavy slabs. Auxiliary vibration adjacent to forms of mass concrete and pavements. May be gang mounted to provide full width internal vibration of pavement slabs.
4	3-6 (8-15)	7000-10500 (120-180)	0.70-2.5 (0.81-2.9)	0.03-0.06 (0.08-0.15)	1500-4000 (680-1800)	12-20 (30-51)	(15-40) (11-31)	Mass and structural concrete of 0 to 2-in. (5 cm) slump deposited in quantities up to 4 cu yd (3 m^3) in relatively open forms of heavy construction (powerhouses, heavy bridge piers and foundations). Also auxiliary vibration in dam construction near forms and around embedded items and reinforcing steel.
5	5-7 (13-18)	5500-8500 (90-140)	2.25-3.50 (2.6-4.0)	0.04-0.08 (0.10-0.20)	2500-6000 (1100-2700)	16-24 (40-61)	25-50 (19-38)	Mass concrete in gravity dams, large piers, massive walls, etc. Two or more vibrators will be required to operate simultaneously to melt down and consolidate quantities of concrete of 4 cu yd (3 m^3) or more deposited at one time in the form.

NOTES:

Column 3	--	While vibrator is operating in concrete.
Column 4	--	Computed values. (1 cm-kg = 0.098 Nm)
Column 5	--	Computed or measured values. This is peak amplitude (half the peak-to-peak value), operating in air.
Column 6	--	Computed values using frequency of vibrator while operating in concrete. (1kgf = 9.807 N)
Column 7	--	Distance over which concrete is fully consolidated.
Column 8	--	Assumes insertion spacing is 1-1/2 times the radius of action, and that vibrator operates two-thirds of time concrete is being placed.
Columns 7 and 8	--	These ranges reflect not only the capability of the vibrator but also differences in workability of the mix, degree of deaeration desired, and other conditions experienced in construction.

however, if it does not, reinserting the vibrator a few inches away should cause closure. If this is not effective, the mixture or the vibrator should be changed.

It is important that the slab be uniformly consolidated. The pattern of insertion depends on the radius of action of the particular vibrator-mixture combination (see Fig. 9).

The radius of action (e) should be determined for the equipment, materials, and conditions existing on the job. Geometry dictates that the distance (D) between vibration points should be $e\sqrt{3}$ or $e\sqrt{2}$ depending on whether a pattern of equilateral triangles (Fig. 9a) or a square grid (Fig. 9b) is employed (*30*). For the same number of immersion points the triangular pattern provides a greater coverage; the square grid, however, provides more thorough compaction (greater area of overlap). Of course, in practice the vibration pattern is not this systematized; however, the concept of insuring thorough and uniform compaction as it relates to the radius of action is important.

When the vibrators are gang mounted for paving, the radius of action is still significant (see Fig. 10). Spacing of the vibrators across the slab is very important and is relative to the forward velocity of the machine, the mix design, and the size of the aggregates and the additives. As indicated in Figure 10a, the maximum spacing coincides with the diameter of effect (twice the radius of action). An overlapped D/E spacing (Fig. 10b) is often advocated; however, to the extent that the directional effects of the individual vibrators counteract each other, the overlapped spacing may be counterproductive. If the spacing exceeds the diameter of effect, voids will occur between the vibrators (see Fig. 10c). In any event, it appears that the compaction of the upper surface between vibrators is less than that in the vibrator path.

PROPERTIES AND PROBLEMS ASSOCIATED WITH VIBRATION

As indicated in Figure 1, the quality of concrete improves when the water-cement ratio is decreased and when consolidation is increased. Vibration per se does not improve the properties of concrete; however, it removes large voids and permits placement of concrete at a lower water-cement ratio than is possible with hand placement. Thus, the improvement of properties attributable to vibration reflects the relationship between voids in the concrete and water-cement ratio. Specific examples of relationships between some properties and various vibrator characteristics are discussed later in this synthesis. Because the interaction of a number of vibrator characteristics defines specific properties, generalization is risky; however, there is general agreement as to certain important relationships.

The relationship shown in Figure 11 between the degree of compaction and resulting strength was developed by Glanville et al. (*32*). In this study, strength ratio is expressed as a function of density ratio. The density ratio is the ratio of actual density of a given concrete to the density of the same concrete mixture if fully compacted. The strength ratio is likewise the ratio of the strength of a partially to a fully compacted mixture. The lowest density ratio represents the state of concrete as deposited without any consolidation. It can be seen that a reduction of about 5 percent of voids is accompanied by a strength increase of about 30 percent. As early as 1897 Feret (*33*) had expressed strength in terms of a relationship involving the sum of volumes and air in hardened paste.

The influence of water-cement ratio and aggregate content on shrinkage is illustrated by Ödman (*34*) (see also Fig. 12) and reported by Neville (*35*). Because vibration enables placement of concrete at both a lower water content and higher aggregate content, the shrinkage of concrete consolidated by vibration is much lower than that of concrete less efficiently consolidated. Although the relationship is shown in Figure 12, in terms of water-cement ratio, shrinkage is in fact a function of total water content of a unit volume of concrete.

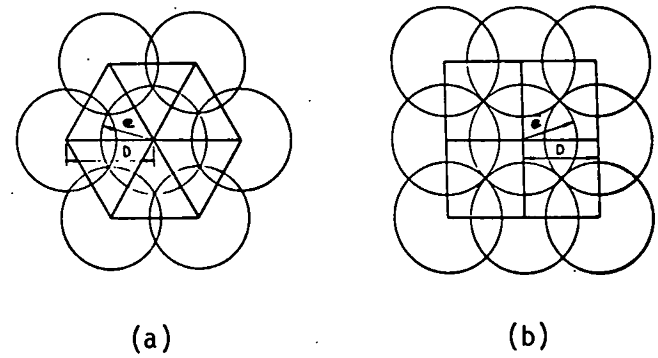


Figure 9. Coverage resulting from different vibrator patterns (30).

Permeability of concrete is primarily a function of consolidation. Wet mixtures used to circumvent the need for mechanical consolidation increase permeability. Powers et al. (*36*) in Figure 13 illustrate the important influence of water-cement ratio on permeability. Obviously, in addition to increased permeability of cement paste of wet consistency, concrete containing large interconnected voids is strongly susceptible to entry by solutions. Thus, permeability is closely related to deterioration by sulfates, freezing and thawing, corrosion of reinforcement, and a number of other disruptive processes.

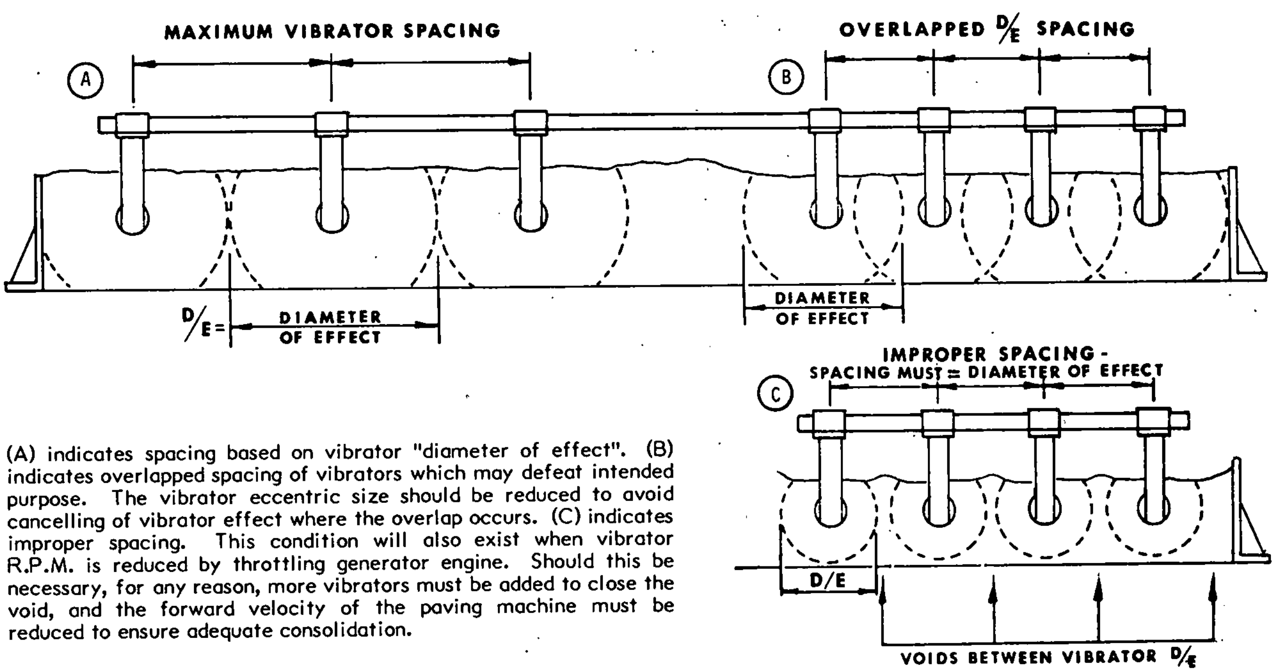


Figure 10. Coverage resulting from gang-mounted internal vibrators (31).

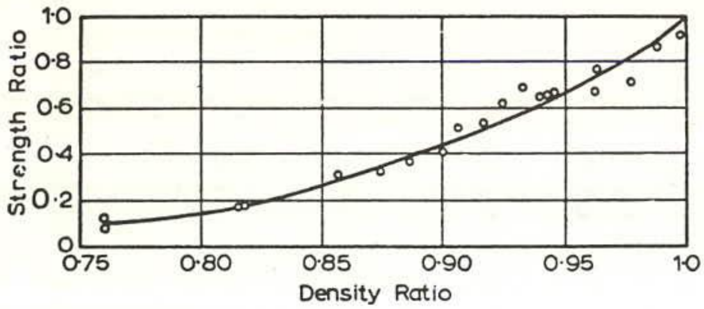


Figure 11. Relation between strength ratio and density ratio (32).

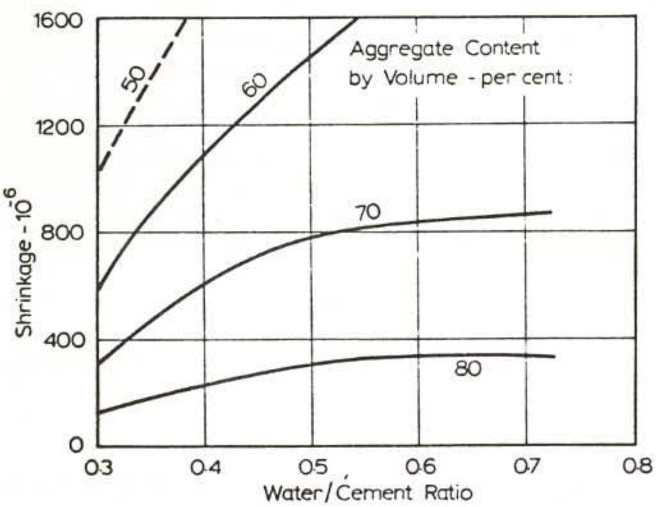


Figure 12. Influence of water-cement ratio and aggregate content on shrinkage (34).

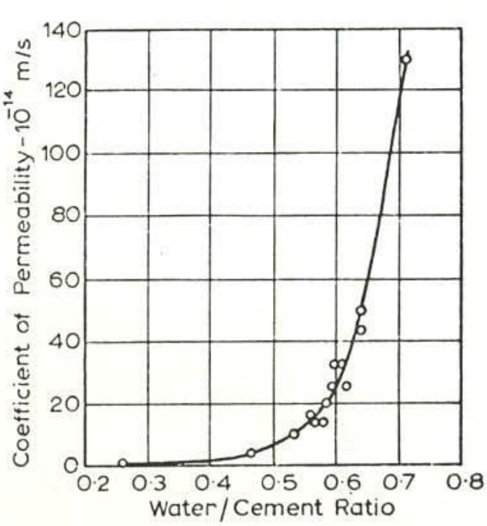


Figure 13. Relation between permeability and water-cement ratio for mature cement paste (93 percent of cement hydrated) (36).

Resistance to freezing and thawing is largely a function of entrained air content, which may be reduced by excessive vibration. As discussed later in this synthesis, evidence supports improved resistance to freezing and thawing even when substantial amounts of entrained air are removed. Resistance to abrasion is primarily a function of compressive strength, which has been shown to increase considerably with density. These relationships are typical of those involving other properties, all of which are improved by proper compaction.

Less definable but more graphic are the results of improper consolidation. The most obvious is honeycombing, such as shown in Figure 14. Figure 15 (*37*) shows an extreme case of segregation where, under extended vibration of wet mixtures, the finer materials are brought to the surface or adjacent to the vibrator.

In reinforced concrete, a primary concern is that proper bond be established between the mortar and the reinforcement. This contact is important not only for strength but also for resistance to corrosion. Improper consolidation can result in voids adjacent to reinforcement in both bridge decks and continuously reinforced pavements, as shown in Figures 16 and 17.

Problems from undervibration and delayed vibration are much more likely to occur adjacent to construction joints in continuously reinforced pavements, where reinforcement is doubled and start-up operations restrict the use of mechanical equipment. Without additional hand vibration, cracking such as that shown in Figure 18 often occurs; other contributing factors are also active, however. Invariably this type of performance is accompanied by voids near reinforcement, also characteristic of undervibration.

From these examples (positive and negative) of the influence of consolidation, it is obvious that proper mechanical vibration is of vital importance to performance.

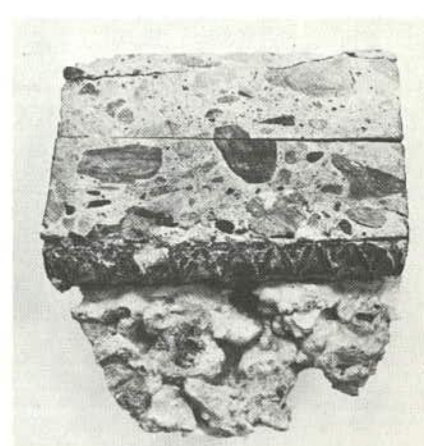


Figure 16. Voids under reinforcing bar caused by poor consolidation of concrete (38).

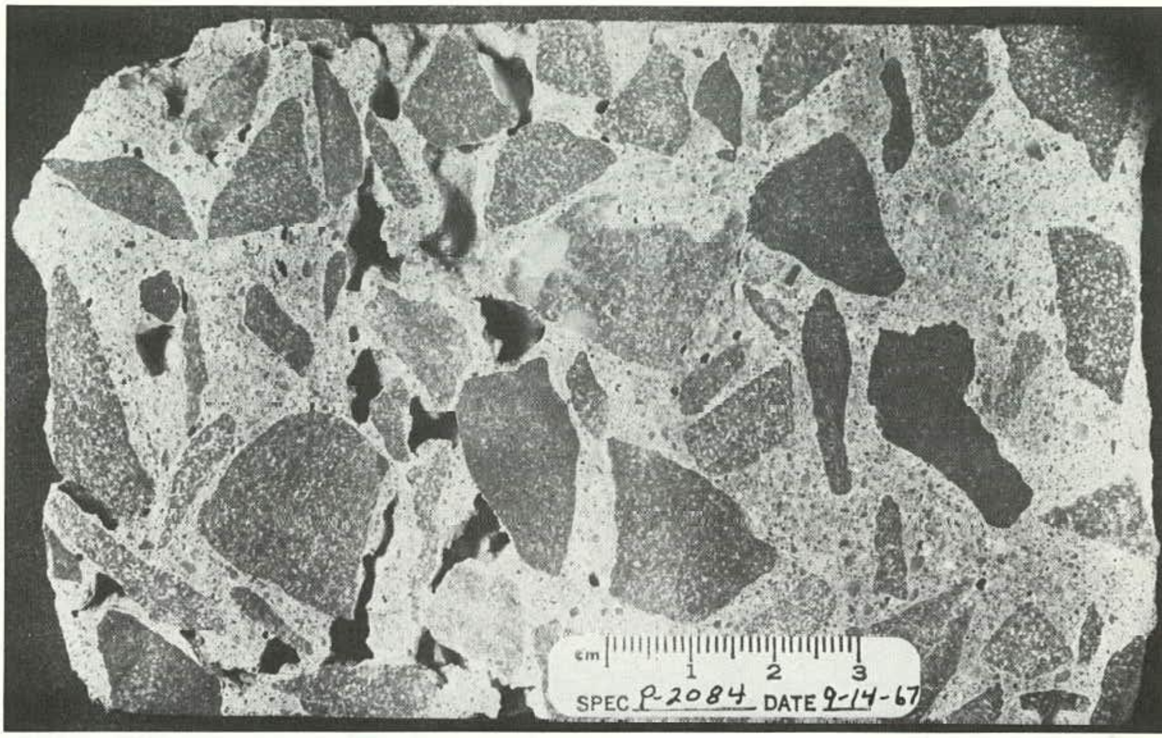


Figure 14. Honeycomb, the result of improper consolidation (37).

Figure 15. Segregation of a mixture improperly proportioned (over-mortared) for the degree of vibration used (37).

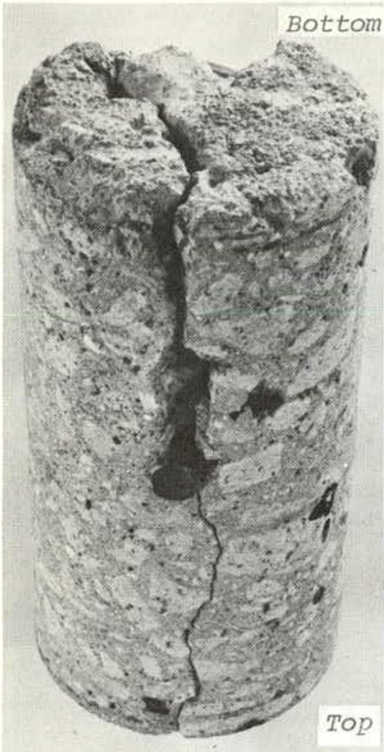


Figure 17. Core taken from a poorly consolidated pavement (39).

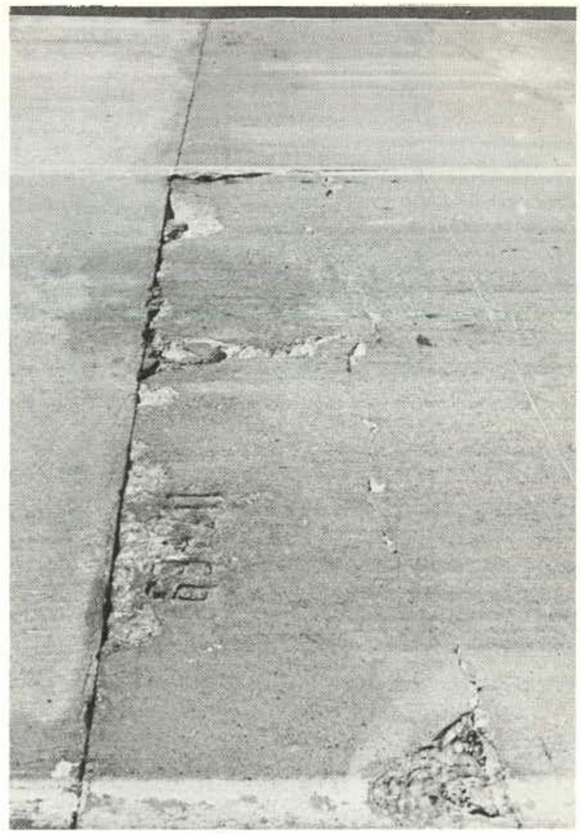


Figure 18. Construction joint failure caused by lack of consolidation (40).

CHAPTER THREE

CONCRETE PAVEMENT

Concrete pavement construction has undergone a significant evolution in the past decade, including development of equipment for high-volume production. Slip-form construction has for the most part replaced form construction. The use of continuously reinforced pavements as well as placement by slip-form pavers is also widely practiced. Coinciding with the changes in pavement design and construction practices have been efforts to update specifications and practices to take advantage of the more rapid and economical procedures without compromising the quality or potential performance of the finished pavement. This concern has resulted in a considerable research effort as well as the gathering of information on current specifications and practices.

Despite early demonstration that the use of vibration was beneficial to concrete pavement construction, there was not a widespread concern for its necessity or improvement until the advent of the slip-form paver, which encouraged use of stiffer concrete than had been required by the earlier types of pavers traveling on forms. Coinciding with the development of slip-form pavers was expanded use of central-plant mixers and significant increases in placement rates. These were accompanied by greater use of continuously reinforced pavements and renewed concern for the riding qualities and durability of pavements subjected to high-volume and high-speed traffic. All of these factors resulted in a greatly renewed interest and research effort on vibration and consolidation of concrete for pavements.

Responding to concerns that had been expressed that pavement concrete might not be receiving optimum consolidation or that segregation might be occurring, several states and the Federal Highway Administration initiated research with primary emphasis on field evaluations. One such project was the National Experimental and Evaluation Program (NEEP) Project 8 entitled "Proper Vibration of Portland Cement Concrete (PCC) Pavements" (*41*). Guidelines for the study to be conducted on regular field paving jobs identified four factors that should be varied and evaluated: (a) speed of paver, (b) frequency of vibration, (c) spacing of vibrators, and (d) weight of vibrator eccentric. Certain tests were recommended and a format for reporting data was suggested. The final summary of this project identified ten states that had directly participated in the NEEP project or had furnished data from other research projects conducted independently but that conformed sufficiently to be included. Of the ten states listed in the final summary (*41*), eight states [Colorado (*42*), Illinois (*43*), Kentucky, Utah (*44*), Texas (*45, 46*), Mississippi (*47*), New York, and Washington (*48*)] conducted field tests and two states [Alabama (*49*) and Indiana (*50*)] undertook laboratory studies. Reports have been issued by all but Kentucky and New York; both states supplied data in the NEEP format without interpretation. The significant variables in these experiments are summarized in Table 3.

In addition to the ten states included in the NEEP summary, five states [California, Florida, Kansas, Virginia (*51*), and Wisconsin] indicated in response to a Transportation Research Board questionnaire (see Appendix) that they had conducted and reported research on vibration of PCC pavements. Significant studies of consolidation or vibration of concrete have also been reported by other agencies such as the U.S. Army Corps of Engineers and several European research groups (*52*).

Despite the effort that has been directed toward identifying under field conditions the factors influencing consolidation of concrete by vibration, the results have not consistently confirmed the relationships that would be expected from theoretical or laboratory studies. This is not surprising; the large number of variables and interrelationships between equipment and concrete make it impossible under field conditions to control the important variables independently. The desire to study large numbers of parameters

TABLE 3

VARIABLES STUDIED IN NEEP STUDIES (*41*)

	STATE	MIXTURES			VIBRATORS			PAVER	OTHER
		Cement Content (lb/yd^3)	Aggregates	Slump (in.)	Spacing (in.)	Frequency (vpm)	Eccentric (Amplitude) (in.)	Speed (fpm)	
FIELD STUDIES	Colorado (Job 1)	611	35% +4 65% sand	1 to 4	9, 12, 15, 21	9,000 10,800	1-7/8, 1-5/8 1-7/16, 1-1/4	10 13 16 19	Nuclear density
	Colorado (Job 2)	564	65% +4 35% sand	1 to 4	12 18 24	4100*, 7000 9000 11,000	1-7/8, 1-5/8 1-7/16 1-1/4		Nuclear density
	Illinois	526	60% +4 40% sand	1-1/4 to 3-1/8	30	7,200* 8,600* 10,000*	1-5/8 1-3/4 1-7/8	6 8.5 12	
	Utah	470	1-1/2 max. (Gravel)		21 24 27	8,000 9,500 11,000	1-1/4 1-7/16 1-5/8 1-7/8	4 7	
	Texas	413			36 30 24	7000** 7800** 9000**			
	Mississippi (Job 1)	526	2-1/2 max.	1-3/4 to 2-1/4	24	7,000 9,000 11,000	1-7/8	10 20	Nuclear density vs. core density
	Mississippi (Job 2)	526	2 max.	1-1/2	24	7,000 9,000 11,000	1-7/8	12 16	Nuclear density vs. core density
	Mississippi (Job 3)	526	1-1/2 max.	3/4 to 1-1/4	24	7,000 9,000 11,000	1-7/8	14 16	Nuclear density vs. core density
	Washington	564			17, 20, 30				Vibrated vs. hand rodded unit wt.; Unit wt. test vs. cores
	Virginia	587	2 max.	1 to 2-3/4		7,800 10,000			
LAB STUDIES	Alabama		#57 #68 #7			4500 5000 7500	(0.04) (0.11) (0.09)		Depth of form (6", 10", 18"); Duration of vibration (2 & 5 sec)
	Indiana		Limestone Limestone Gravel			Varied 7,000 - 13,000			Duration of vibration (5 and 13 sec.) Nuclear density (backscatter)

* In situ

** Surface pan vibrator used with internal vibrators

1 lb/yd^3 = 0.59 kg/m^3 1 fpm = 0.3 m/min

1 in. = 25.4 mm

combined with the inherent variability of field concrete and test methods would require prohibitively large numbers of specimens. Practical limits on the number of tests reduce the ability to draw statistically valid conclusions. Thus, in most of the field studies, few differences in the properties of concrete were found despite comparatively large differences in vibrator characteristics and uses.

Despite the apparent lack of conclusive results, when the results from the various field studies are considered in the light of theory and laboratory studies, certain trends are clear and other tendencies suggest procedures that can be used to improve consolidation of paving concrete.

PROPERTIES OF CONCRETE AFFECTING CONSOLIDATION

Effect of Slump on Consolidation

There is general agreement that the consistency of concrete as reflected by slump is a very important factor in determining the amount of compaction achieved. Colorado initially demonstrated that lower densities were obtained when slumps were either too high or too low (*42*). Optimum consolidation was obtained with concrete with approximately a 2-in. (50-mm) slump. Results from research on two paving projects in Colorado using different mixtures and different paving equipment are shown in Figure 19.

Studies from Indiana (*50*), Illinois (*43*), Mississippi (*47*), and Virginia (*51*) confirmed either directly or indirectly the Colorado experience. There is general agreement that concretes with slumps less than approximately 1 in. (25 mm) or more than approximately 2¼ in. (55 mm) do not respond well to consolidation by vibrators commonly available. The relationship shown in Figure 19 is confirmed by theoretical and laboratory studies, which show that when extremely low-slump concrete is internally vibrated, more energy in the form of longer vibration times, higher frequencies, or larger amplitudes is needed than when the consistency is wetter. Higher-slump or wetter concrete, on the other hand, results from inclusion of more of the lighter component, water, as compared with the heavier solids than does lower-slump concrete. Thus, by definition it results in a less dense mixture. Higher-slump concrete is also most susceptible to excessive loss of beneficially entrained air, creation of bleed channels, and detrimental segregation. In several states, variation of slump was cited as a probable reason for lack of definitive results from other tests and observations.

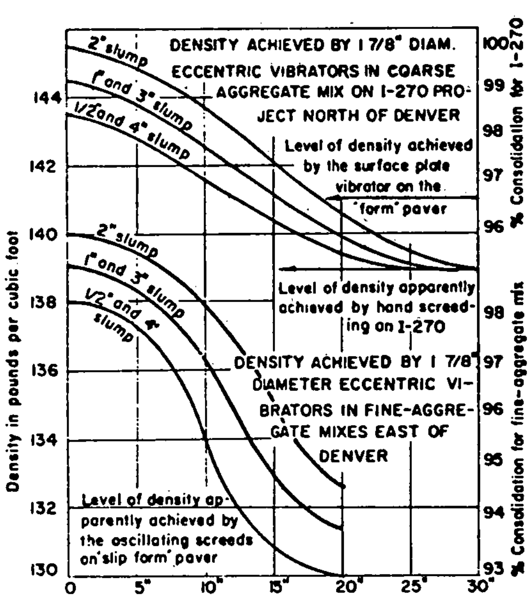


Figure 19. Density as a function of slump and vibrator spacing (42).

Effect of Mixture Proportions

Two of the field studies and the two laboratory investigations noted earlier included mixture proportions or types of aggregate as variables. Colorado found more and larger voids with the finer mixture that had a rodded density of 140 pcf (2 250 kg/m³) than with the coarser mixture that had a rodded density of 146 pcf (2 350 kg/m³). As shown in Figure 19, there was no significant difference in the fraction of this rodded density achieved in the field. Mississippi, Alabama, and Indiana found no significant differences of consolidation within the range of mixtures studied except as reflected in the variations of slump. This is not to say that mixture proportions are unimportant but rather that all of the mixtures used were adequately proportioned for the conditions to which they were exposed.

The requirements for durability, strength, and volume stability dictate mixture proportions. Because all of these properties are beneficially affected by lower water contents, the emphasis is on stiffer mixtures. Placeability, on the other hand, improves with wetter consistencies. Generally speaking, mixtures made with small maximum-size aggregates and high sand contents provide more workability than is needed for the type of equipment used to consolidate pavements.

In an extensive review of available research, Popovics (*53*) concluded "that the optimum composition of concrete for consolidation by vibration is not quite identical with that for consolidation by a less efficient procedure." Because of its stiffer consistency, a vibrated concrete may have (a) aggregate grading somewhat coarser and (b) solids content somewhat greater than the comparable concrete consolidated by hand. Popovics also observed that overly stiff mixtures could not be effectively consolidated by hand, quoting research by Bergström, which showed that when concrete contains an excess amount of coarse aggregate some of the particles will remain loose on top of the mass during vibration. Popovics further concluded that a small excess of mixing water was less harmful than a comparable lack of water. In addition, the greater the difference between the density of the coarse aggregate and the density of the mortar and the wetter the consistency, the more likely the occurrence of internal segregation.

There is some experimental and field evidence to indicate that mixtures made with gap-graded aggregates are more easily compacted than those made with aggregates having continuous gradings; those with gap-graded aggregates require closer attention and may be prone to segregation, however. In a report of extensive studies of gap grading, Li and Kamakrishnan (*83*) stated that "the vibration time required for gap-graded concrete is less than that for continuously graded concrete for all cement contents, water-cement ratios, and maximum sizes of coarse aggregate throughout this investigation. This should mean that gap-graded concrete is more workable and requires less energy for full compaction than does continuously graded concrete having the same mix parameters." This finding is not generally accepted in the United States and gap grading has not found wide use in this country. Where economics or local aggregate characteristics dictate use of gap grading, it offers potential advantages in stiff mixtures that are to be consolidated by vibration.

Influence of Base

Few published data were found relating the influence of base to the density of slabs consolidated by internal vibration; however, improved properties from surface vibration with increased rigidity of base have been demonstrated.

Consolidation depends on the action of gravity to settle particles that have been separated under the influence of compression waves moving through the mixture. In the cases reported later in this chapter under "Vibrator Spacing" (see Table 4 also), the bottom of the pavement showed greater density and strength than the surface. This is partially explained by the upward migration of the lighter constituents of the mixture.

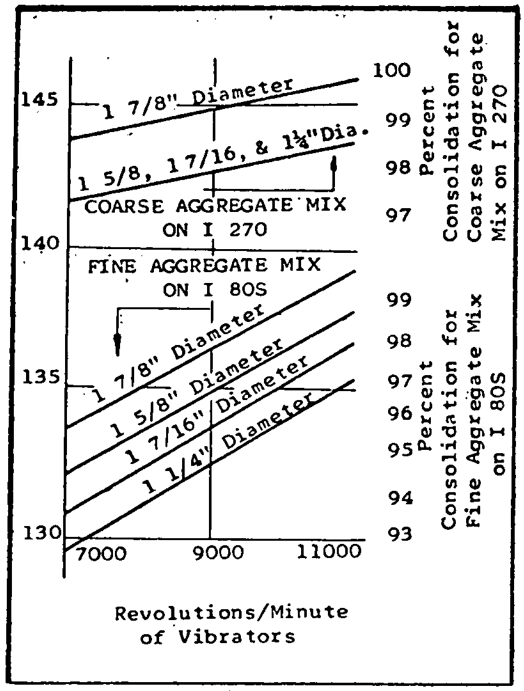


Figure 20. Influence of frequency and eccentric size on density (42).

EQUIPMENT PROCEDURES AFFECTING CONSOLIDATION

Effect of Frequency

A major focus of the recent field and laboratory research projects has been to study the influence of vibrator frequency on consolidation and the resulting properties of concrete. Frequency can be stated as revolutions per minute (rpm), cycles per minute (cpm), or vibrations per minute (vpm, or hertz). The frequency measures used in this synthesis reflect the term used in each study under discussion. Reference to frequency is sometimes clouded by failure to distinguish between the frequency of vibration in air and the corresponding frequency, reduced by about 15 percent, in concrete.

According to studies in Colorado, density for both the fine and coarse mixtures increased with frequency over the range from 7,000 to 11,000 rpm as shown in Figure 20.

The relationship was confirmed by Indiana studies, which found that frequencies of 10,800, 12,000, and 13,200 cpm were more effective than those of 7,200 and 9,600 cpm. Illinois found that increases of frequencies between 7,200 and 10,000 rpm resulted in increased density of the lower half of cores. These studies also suggested a tendency for increased segregation and air loss with increased frequency. Results obtained in Mississippi showed that 100 percent of theoretical density was obtained at all frequencies within the range of 7,000 to 11,000 vpm, but above 9,000 vpm there was a slight tendency for lower density. It is interesting to note in Figure 20 that the frequency influenced the finer mixture more than the coarse mixture. No significant influence of frequency was indicated by other studies. The existence of an optimum frequency, such as found in Mississippi, above which the efforts of vibration are reduced is consistent with findings reported by Forssblad (*21*), who found that the radius of action and likewise the resulting compaction at a given location varied with frequency as shown in Figure 21. The optimum frequency occurs at a lower frequency for larger amplitudes. This suggests that stiff concrete is too sluggish to respond to more rapid and larger vibrating forces, which create a "postholing" effect with correspondingly reduced compaction. There are also theoretical bases and some experimental data to support the existence of a resonant or natural frequency of a concrete mass at which a given force is more effective in compacting the material. The resonant frequency would depend on the specific components and proportions. Although concrete is a heterogeneous material, the over-all combination has a reasonable amount of resonance. Some data suggest that the resonant frequency of fresh concrete is about 10,000 vpm. There are also data indicating that the attenuation coefficient or the reduction in radius of action decreases with increasing frequency (*28*). All of the factors combine to support the validity of an optimum frequency.

Some vibrators have been built with very high frequencies (in the range of 12,000 to 20,000 vpm) but these have not performed as well as anticipated (*54*). It is probable that the optimum frequency can vary depending on the characteristics of equipment and of concrete over a range approximately comparable to those included in the various field studies. All were greater than the minimum value of 7,000 to 8,000 vpm recommended by ACI and included in many specifications for this type of vibrator.

It thus appears that internal vibrators with a frequency

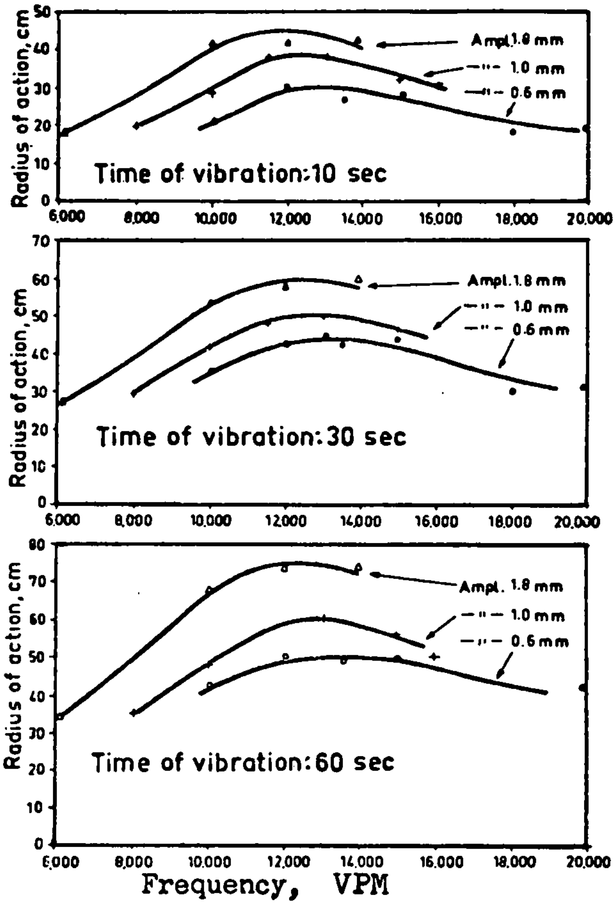


Figure 21. Relationship between the radius of action, frequency, and amplitude during different times of vibration; diameter of the vibrating heads: 2½ in. (60 mm), concrete consistency: 6 Vebe degrees (21).

greater than approximately 7,000 vpm provide adequate consolidation. The effectiveness of consolidation improves with an increase in frequency to approximately 10,000 vpm, depending on the characteristics of the vibrator and of the concrete mixture. There is some evidence that frequencies greater than approximately 13,000 vpm are less effective than lower frequencies. Apparently most of the data on which these statements are based result from frequency measurements made in air. The corresponding values in concrete would be reduced by about 15 percent.

In some areas, economically available aggregate sources contain lightweight particles in amounts sufficient to cause them to accumulate on the surface at frequencies above about 6,000 vpm. Where such aggregates are used, lower frequencies are often employed.

Effect of Amplitude

As noted earlier, amplitude is largely a function of the eccentric moment and of head weight. However, because eccentric distance is more easily determined, most of the results summarized in this synthesis are from studies that used the values for eccentric distance rather than amplitude. To convert the eccentric distances to amplitude would require information about the vibrators that is unavailable. Those wishing to pursue the subject further should be aware of the important distinction between amplitude and eccentric distance.

The effectiveness of an internal vibrator depends on the head diameter, frequency, and amplitude. There is no simple way to measure amplitude of the portion of the vibrator that is in concrete. Visual scales (discussed later in this chapter) give good results, but are really giving amplitude only at the location where they are attached and, of course, can not be read in the concrete.

The Indiana study (*50*) attempted to obtain a direct measurement of amplitude in concrete. As reflected in the report, the measurement of amplitude was difficult but was highly correlated with input frequency. No large influence of amplitude was observed, although one conclusion was that an amplitude range between 0.0045 and 0.0055 in. (0.11 and 0.14 mm) should be used. These amplitudes appear to be low when compared with other findings, such as those shown in Figure 21.

A certain minimum amplitude is necessary for the vibrator to be effective in setting the particles within the concrete mixture in motion. The data developed in Colorado and by Forssblad (presented in Figures 20 and 21, respectively) indicate increased compaction or radius of action with increased amplitude (eccentric diameter). The influence was greater for the finer mixture than for the coarser mixture (see Fig. 20). Studies in Illinois generally confirmed increased density distance or amplitude (*43*). Other studies, obtaining satisfactory consolidation, use a constant large eccentric [1⅞ in. (40 mm)]. The increased force associated with increased eccentric has been demonstrated by Wilde (*29*).

Paver Speed (Duration of Vibration)

As indicated previously, consolidation is a two-stage process. The major densification occurs quickly in the first stage as the particles are packed. This stage is followed by a much-reduced rate of densification as the entrapped and larger entrained air voids are removed. The amount of consolidation is a function of the duration of vibration. ACI recommends that internal vibrators be held in place from 5 to 15 sec. With a paver that operates with a continuous forward motion, the duration of vibration at a given point is a function of paver speed. If one assumes an effective length of 1 ft (0.3 m), the paver speed corresponding to a vibration time of 5 and 15 sec would be 12 and 4 feet per minute (fpm) (3.6 and 1.2 m/min), respectively. All recent field or laboratory studies have included either paver speed or duration of vibration as a variable.

On the basis of measurements in the laboratory, Alabama's study showed that settlement of concrete with ¾-in. (19-mm) slump was about 90 percent complete in 5 sec, whereas settlement of 1¾-in. (45-mm) slump concrete was essentially complete in 3 sec (*49*). The latter value corresponds to a paver speed of about 20 fpm (6 m/min). Indiana found that 7 sec of vibration with a frequency of 12,000 cpm gave the highest mean density (*50*). No significant differences of consolidation were found in studies in which the paver speed was below 12 to 14 fpm (3.6 to 4.3 m/min); no evidence of overvibration was reported. Only two states (Colorado and Mississippi) conducted tests at speeds approaching 20 fpm. Colorado reported a slight indication of loss in density with increased speeds greater than 16 fpm (4.9 m/min) (*42*). Teng (*47*), presenting results from studies in Mississippi, reported no large influence of paver speed. He noted, however, that if the data were to be corrected for the influence of slump, a somewhat lower density would be indicated at 16 and 20 fpm than for 10, 12, or 14 fpm. Walker (*55*), reporting the results of void-content measurements on cores taken in Virginia from a pavement on which paver speed had been varied, found higher void contents in the upper half of the cores under a combined influence of increased paver speed and increased distance from the vibrator path, as shown in Figure 22. At speeds of 3, 4¼, and 5½ fpm (0.9, 1.3, and 1.6 m/min), the void contents were approximately the same regardless of distance from the vibrator path. At speeds of 11, 12, and 14 fpm (3.3, 3.6, and 4.3 m/min), cores more than 6 in. (150 mm) from the vibrator path contained significantly more voids than did the cores in the vibrator path or cores consolidated at lower speeds.

It appears that adequate consolidation can be obtained with conventional paving equipment using internal vibration and large vibrators [approximately 1⅞-in. (40-mm) eccentric distance] at speeds up to approximately 20 fpm (6 m/min). Speeds greater than 14 to 16 fpm (4.3 to 4.9 m/min) will result in reduced density.

Vibrator Spacing

The radius of action can be expected to dictate vibrator spacing necessary for proper compaction. For complete coverage (see Figs. 9 and 10), the spacing should be somewhat less than twice the radius of action. As given in Table 2, for the type of vibrators normally used in pavements, the radius of action recommended by ACI Committee 309 is from 7 to 14 in. (180 to 360 mm). Most specifications refer to full-width vibration but comparatively few require a specific maximum spacing. A common spacing is 24 to 30 in. (600 to 760 mm). Many recent field studies include spacing as a variable. In addition, most projects involve sampling in the path of the vibrator as well as between vibrator paths. These results provide some insights into the effect of distance (spacing) on consolidation. As indicated in Table 4, in every case the density and strength were greater in the paths of the vibrator than between paths. In general, differences of density were approximately 1 to 2 pcf (16 to 32 kg/m^3) and differences in strength were about 10 percent. In most cases, the differences were most pronounced in the upper portion of the pavement. The pattern of results is consistent with the coverage as shown in Figure 10.

Walker (*51*) also observed more voids (reduced density) with increasing distances from vibrators that were spaced 24 in. (600 mm) apart. Walker attempted to reflect the influence by computing a "consolidation factor" defined as:

$$\mathrm{CF} = (d_1\, d_2\, Sr)/Sl \qquad (3)$$

in which

CF = consolidation factor;
d_1 and d_2 = distances to nearest vibrator, in. (mm);
Sr = relative speed, or $\dfrac{\text{test forward speed}}{\text{lowest forward speed}}$; and
Sl = slump, in. (mm).

No theoretical basis for the consolidation factor was proposed; however, it reflects the comparative influences of distance from the two vibrators nearest the core as well as paver speed and slump, all of which affect consolidation. The greater the value of CF, the less the consolidation effort. A good relationship between log CF and the void content of cores is shown in Figure 23 (*51*). On the assumption that a reasonable void content for fully compacted air-entrained concrete would be between 5 and 7 percent, an acceptable CF was defined as between 0.2 and 2.0. The relationships in Figure 24 were developed by solving for various speeds, slumps, and vibrator spacings.

It is clear that these relationships are approximate and qualitative; based on the implications from other projects, however, they seem to be useful first approximations. For example, for slumps between 1 and 2½ in. (25 and 60 mm), a 24-in. (600-mm) spacing would require paver speeds of between 6 and 15 fpm (1.8 and 4.5 m/min). These values approximate the range of values included in the various field trials. As paver speeds approach 20 fpm (6 m/min), the need to reduce vibrator spacing to 18 in. (450 mm) is indicated. Likewise, a 30-in. (760-mm) spacing would be acceptable for paver speeds in the 4- to 8-fpm (1.2- to 2.4-m/min) range. The values are compatible with the radii of action given in Table 2, which suggest that a spacing of 24 in. is nearing the upper limit for effective consolidation. The values in Figure 24 are suggested for relatively uniform consolidation. In most of the projects summarized in Table 4, there is a distinct lowering of density and strength in the upper levels of the pavements between the vibrators. This reduction is expected because, in general, the spacings exceeded those suggested in Figure 24 for speeds in the 12- to 20-fpm (3.3- to 6-m/min) range. From geometrical relationships shown in Figure 10 it can be calculated that with a radius of action of 14 in. (350 mm) a maximum spacing of about 26 in. (660 mm) for an 8-in. (200-mm) pavement or 24 in. for a 9-in. (225-mm) pavement is needed. If the radius of action or the duration of vibration is less, a closer spacing is indicated.

Depth and Angle of Vibrator

Studies in Colorado resulted in a change of the angle of vibrators from 0 (horizontal) to 30° during paving operations. No difference in consolidation of concrete could be attributed to the change of angle as long as the entire vibrator was within the concrete. It was concluded that vibrators appeared to provide the best consolidation when they were in a horizontal position midway between the base and top of the surcharge. This confirms the ACI recommendation that for pavements up to 10 in. (250 mm) thick vibrators should be operated parallel with or at a slight angle to the base. For pavements greater than 10 in., vibrators should be angled toward the vertical with the

TABLE 4

PROPERTIES FOR SAMPLES TAKEN BETWEEN AND IN PATH OF VIBRATORS

State	Density, pcf[1]		Strength, psi[2]	
	In Path	Between	In Path	Between
Colorado, top			4691(c)[3]	4208(c)
Job 1, bottom			5384(c)	5132(c)
(Fine) over-all	138[4]	136[4]		
Colorado, top			4125(c)	3687(c)
Job 2, bottom			4543(c)	3992(c)
(Coarse), over-all	144.5[4]	143[4]		
Illinois, top	138.6	136.5	5204(c)	4774(c)
bottom	140.9	137.3	5521(c)	5375(c)
Mississippi, top	146.4	145.4	-	-
bottom	146.7	145.6	-	-
over-all	148.1[5]	145.9[5]		
Texas, top	141.5[7]	140.8[7]	524.6(f)[6]	493.3(f)
bottom	142.7[7]	141.0[7]	594.9(f)	580.7(f)
over-all	142.1[7]	140.9[7]	560.8(f)	537.7(f)
Washington	149.6	148.4		

[1] 1 pcf = 16 kg/m³

[2] 1 psi = 6.89 kPa

[3] (c) = compression

[4] varied with eccentric distance

[5] nuclear density of top 2 in. (50 mm) of fresh concrete

[6] (f) = flexure

[7] hardened cores

vibrator tip preferably about 2 in. (50 mm) from the base and the top of the vibrator a few inches below the pavement surface. This configuration is difficult where the pavement includes transverse steel. ACI further recommends that a 4- to 6-in. (100- to 150-mm) surcharge of concrete should be carried over the vibrators during placing operations. Greater surcharge loads are likely to cause surging behind the screed or extrusion plate and to prevent full release of entrapped air.

In reinforced pavements a primary consideration in positioning the vibrators is the location of the reinforcement, which is usually slightly above mid-depth. The ability to position vibrators at mid-depth depends on the method of re-bar support and the presence of transverse reinforcement; L-shaped spuds are available that are especially adapted to operating above the mesh in reinforced pavements. Accidental contacts of short duration between vibrator and reinforcement are not harmful. Care must be taken to ensure that the reinforcement remains at the intended location.

Overvibration or Undervibration

The American Concrete Institute (ACI) defines overvibration as "excessive use of vibrators during placement of freshly mixed concrete, causing segregation and excessive bleeding" (*56*). For pavements, the accumulation of high water-cement-ratio mortar, often in the form of foam at the surface, is particularly undesirable. ACI Committee 309 suggests periodic examination of cores to determine the thickness of the surface mortar layer above the coarse aggregate. Thicknesses in excess of ¼ in. (6 mm) indicate either overvibration or overfinishing. Excessive voids in the concrete indicate the need for additional vibration or a change in location of the vibrators.

As noted earlier, no significant segregation was noted in the several field projects. This is not surprising because the concrete used was predominantly of low slump. ACI Committee 309 further states that "undervibration is far more common than overvibration. Normal-weight concretes which are well proportioned and have the recommended

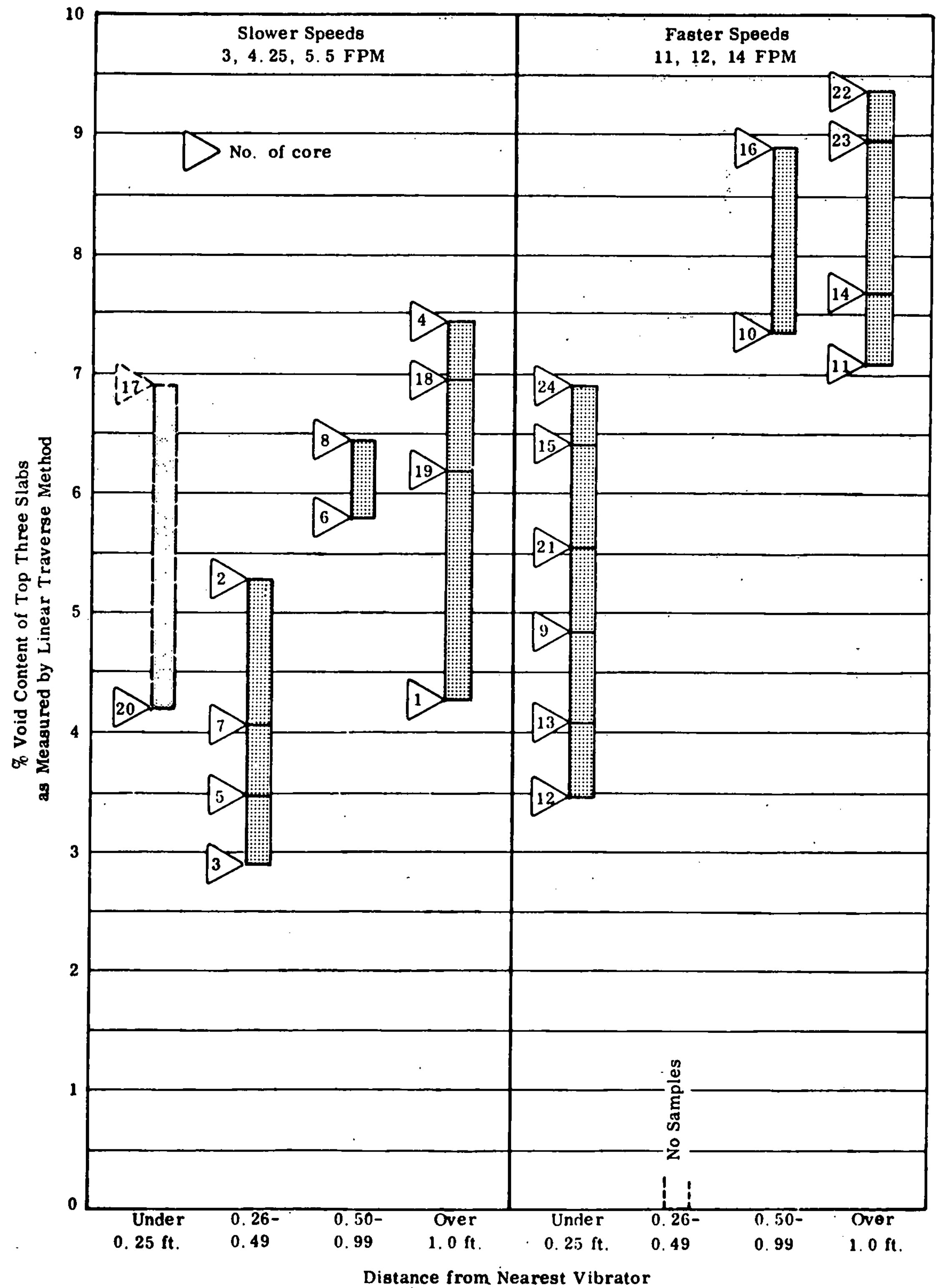


Figure 22. The effect of distance from the nearest vibrator and speed of paver on void content (55).

slump are not readily susceptible to overvibration. Consequently, if there is any doubt as to the adequacy of consolidation, it should be resolved by additional vibration" (*1*). According to McCullough (*57*), problems due to undervibration of continuously reinforced concrete pavements are more common than those due to overvibration.

Problems caused by overvibration are much more likely to occur in wet mixtures. In like manner, undervibration is much more likely in overly stiff mixtures. Proper control of consistency alleviates problems of both over- and undervibration. Unfortunately, whenever segregation, excessive surface fines, or other evidences of overvibration are observed, the initial reaction is to reduce vibration. The proper solution is to adjust the mixture.

Surface Vibration

Most recently published research on consolidation of pavements by mechanical vibration has dealt with internal vibration. Early research in the United States, however, was primarily concerned with surface vibration (*8-16*).

The most extensive research on surface vibration was conducted at the Road Research Laboratory by Kirkham and White (*20*) in the late 1950s. Specially built equipment that permitted the characteristics of the vibrating pan to be varied was used in conducting a series of experiments to study both the characteristics of the equipment and the properties of the concrete mixture. From these studies Kirkham and White concluded that the main factors affecting the performance of the machines were (a) amplitude, (b) number of vibrations transmitted to the concrete, and (c) force on the concrete. These are similar to the factors affecting performance of internal vibrators previously described. Surface vibration can, of course, only be applied on the surface and is, therefore, quite directional. Thus, the critical question is the depth to which compaction can be achieved.

Kirkham and White found that depth was related to the product of the force on the concrete, the amplitude of vibration, and the frequency of vibration, divided by the forward speed of the machine. The force on the concrete was determined to be related to the rise of the beam when

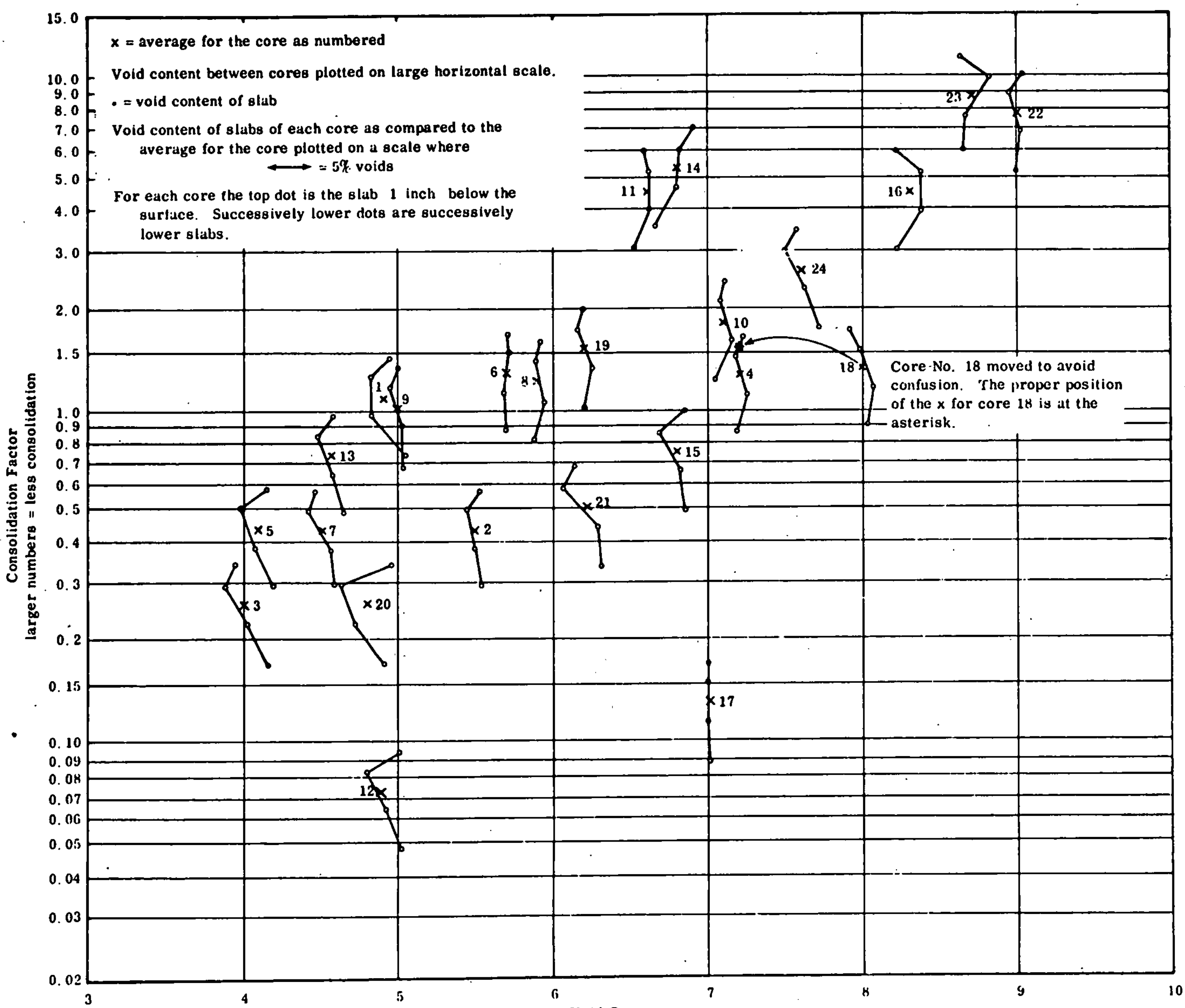


Figure 23. Change in void content with depth versus consolidation factor (51).

vibrating in concrete in relation to its level when vibrating freely in air. The performance of the machine was not greatly affected by either the acceleration of the vibrating beam or its width. The depth of good compaction was affected by (a) the workability of the concrete and the grading of the aggregates, (b) the amount of surcharge provided, (c) the thickness of the slab, and (d) the rigidity of the base on which the concrete was placed. Typical distributions illustrating the results from this study are shown in Figures 25 and 26.

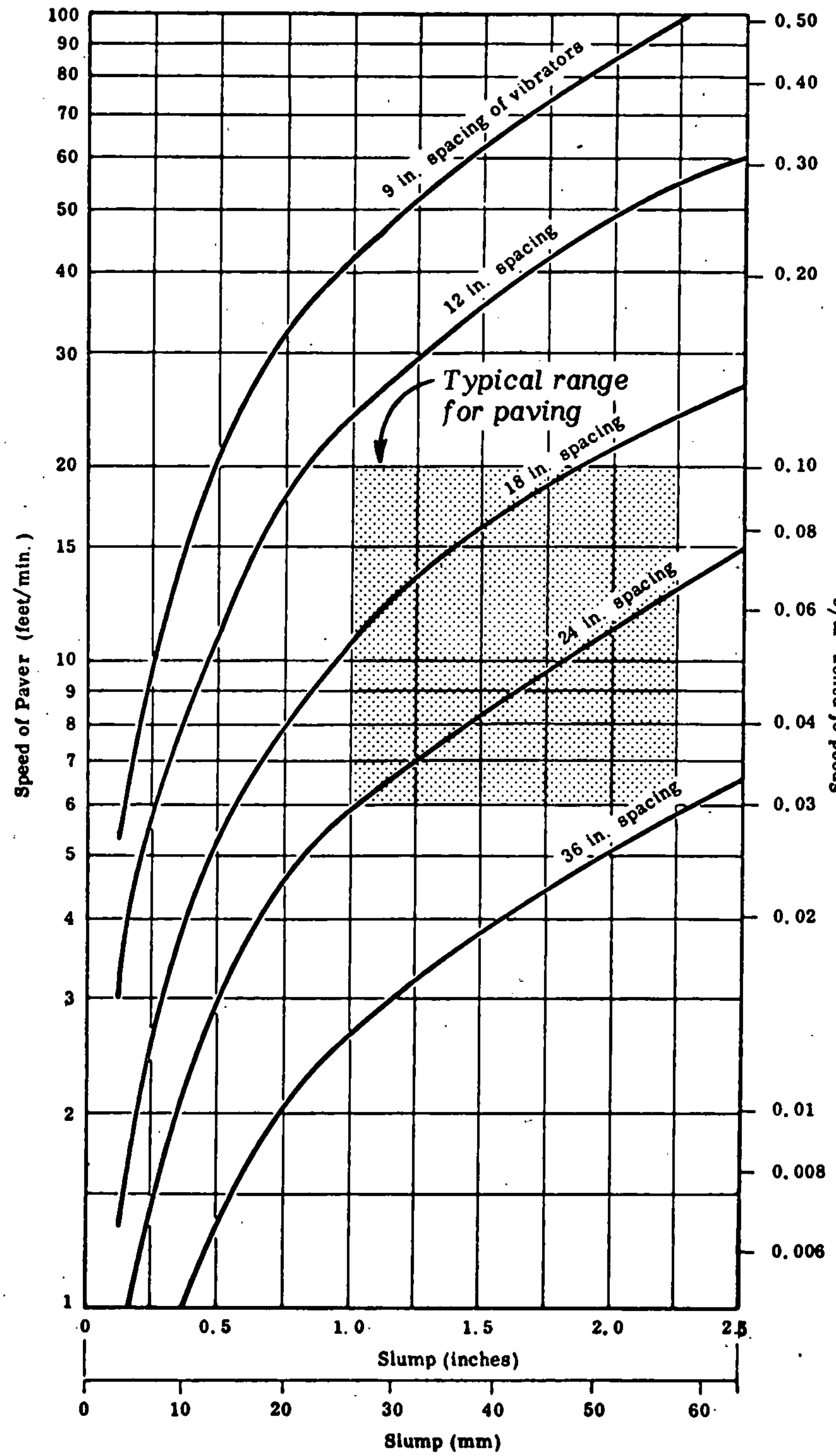


Figure 24. Hypothetical graph of speeds not to be exceeded if consolidation factor is not to exceed 2.0 (51).

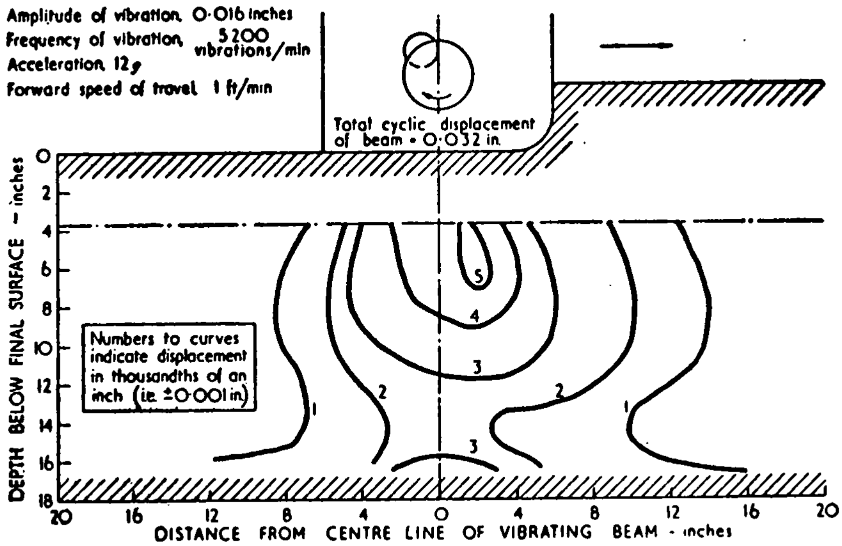


Figure 25. Distribution of displacement in wet concrete under surface vibrator (20).

Figure 25 shows that the influence of vibration is somewhat greater in the unconsolidated concrete than behind the paver after consolidation. The major influence is in the upper 8 in. (200 mm) of the pavement. Under some conditions a slightly increased amplitude was found near the bottom, which was due to reflection of the vibration from the base. Because of this reflection the amount of compaction obtained in a very thick slab (such as used in these tests) would be less than the thickness of slab that could be fully compacted. A typical change of density with compaction is shown in Figure 26, which also shows the influence of thickness on the degree of compaction achieved. The thickness of the test slab was intentionally greater than could be fully compacted throughout the full depth.

When the slab was 18 in. (450 mm) thick the concrete was only fully compacted to a depth of about 3 in. (75 mm) and a similar depth of compaction was achieved in a slab 12 in. (300 mm) thick. Reduction of the slab thickness to 11 in. (275 mm), however, resulted in an increase in the depth of full compaction to approximately 4 in. (100 mm) and in a slightly higher density below this depth than that at corresponding depths in thicker slabs. When the normal thickness of the slab was reduced to 9½ in. (240 mm), there was a considerable surge of the concrete behind the vibrating beam. The maximum depth of well-compacted concrete increased with reduced thickness because of the reflection of the vibration from the base. The density near the surface of the slabs was slightly less than the maximum values obtained at greater depths (see Fig. 26).

Kirkham and White made no comment on this reduction, but it undoubtedly represents the upward migration of water and cement paste toward the surface. When the surcharge provided was smaller than the optimum that the vibrator could compact, the force on the concrete was decreased, resulting in a reduction of the thickness of well-compacted concrete. At the same time, however, the condition of having too much surcharge must be avoided; this dampens the vibrations. The findings of the Kirkham study in Reference (*20*) demonstrate the importance of careful control of the workability of the concrete; wetter concrete resulted in a reduction in the equivalent depth of well-compacted concrete. The basic measure of workability in these tests was the "compacting factor." The compacting factor is defined as the ratio of the weight of concrete allowed to fall into a standard container to the weight of fully compacted concrete filling the same container. It was concluded that for effective surface vibration the compacting factor should be below 0.82. This compacting factor corresponds to a Vebe time of about 4 sec, which is defined in Table 1 as stiff plastic and equivalent to a slump of about 1 to 2 in. (25 to 50 mm). Fortunately, this is the same range of slump that is most responsive to internal vibration. Surface vibration alone is usually not recommended for slabs greater than 8 in. (200 mm) thick.

Research and experience have shown that surface vibration should be supplemented by internal vibration adjacent to forms and load transfer devices. Surface vibration is also a good supplement to internal vibration. For example, on a portion of Interstate 270 studied in Colorado a surface pan vibrator operating at 4,100 vpm was used in addition to the two internal vibrators that were the major variables of the equipment. In a similar study of Interstate 80S only internal vibration was used. As shown in Figure 27, although on both jobs there was a lower density between internal vibrators than in the path of the vibrators, the differences in density between the two locations were lower for the job on which the surface pan was also used, particularly as the vibrator spacing was increased. (As noted previously, the concrete mixtures and other factors of the two projects were also different.)

Oscillating screeds impart some consolidation to the surface of the concrete but are not designed to provide consolidation to any significant depth.

MESH DEPRESSORS

Development of mechanical methods for steel placement has accompanied the increased use of slip-form construction. Scholer and Olateju have summarized these methods in Reference (*58*). Mesh depressors facilitate depression of the reinforcement by vibration and pressure. Because some of this equipment uses vibrations in the range of 2,000 to 4,000 cpm with amplitudes of ⅛ in. (3 mm), it imparts some consolidation to the concrete. The installation takes from 10 to 18 sec and purportedly eliminates the need for more extensive vibration of the concrete after the initial depression cycles. Although this point has not been extensively researched, its influence should be considered when such equipment is used.

OTHER PROPERTIES OF CONCRETE AFFECTED BY VIBRATION

Properties of Hardened Concrete

As has been demonstrated by both field and laboratory research, mechanical properties such as strength, density, and abrasion resistance are improved by proper vibration. Although statistically significant relationships between these improvements and individual characteristics of the vibrators are not always demonstrable, the combined effects from vibration are clearly beneficial. Within the range of variables reported, improvement of these properties by 10 to 15 percent has been observed. It should be noted, however, that all of the studies used equipment and procedures that fulfill the minimum requirements of most specifications and the ACI "Recommended Practice for Consolidation of Concrete" (*1*). Improvement with respect to poorly consolidated concrete would obviously be significantly better. By the same line of reasoning, use of vibration permits using mixtures with lower water-cement ratios, further enhancing all properties as compared with the wetter concrete necessary with less energetic methods. ACI Committee 211 indicates a possible reduction in slump of approximately 1 in. (25 mm), which corresponds to a reduction in water content of about 10 percent for vibrated concrete. In addition to improving strength and durability, the lower water content also reduces volume changes from shrinkage and creep. The effects of many destructive processes, including those from corrosion of reinforcement, sulfate attack, and freeze-thaw, which depend on entry of water or solutions into the concrete, are significantly reduced by proper and thorough vibration.

Because freeze-thaw resistance and resistance to scaling from deicing chemicals are primarily a function of the presence of adequate amounts of entrained air, there is some concern that excessive vibration and the accompanying loss of air will detrimentally affect freeze-thaw resistance. Backstrom et al. (*26*) found that air-entrained concrete retained its characteristic frost resistance even after expulsion by extended vibration of a large portion of its air content. ACI Committee 212 (*59*) stated that "resistance of concrete to laboratory freezing and thawing has not been found to be affected adversely by loss of air as a result of vibration, provided that the concrete originally contained

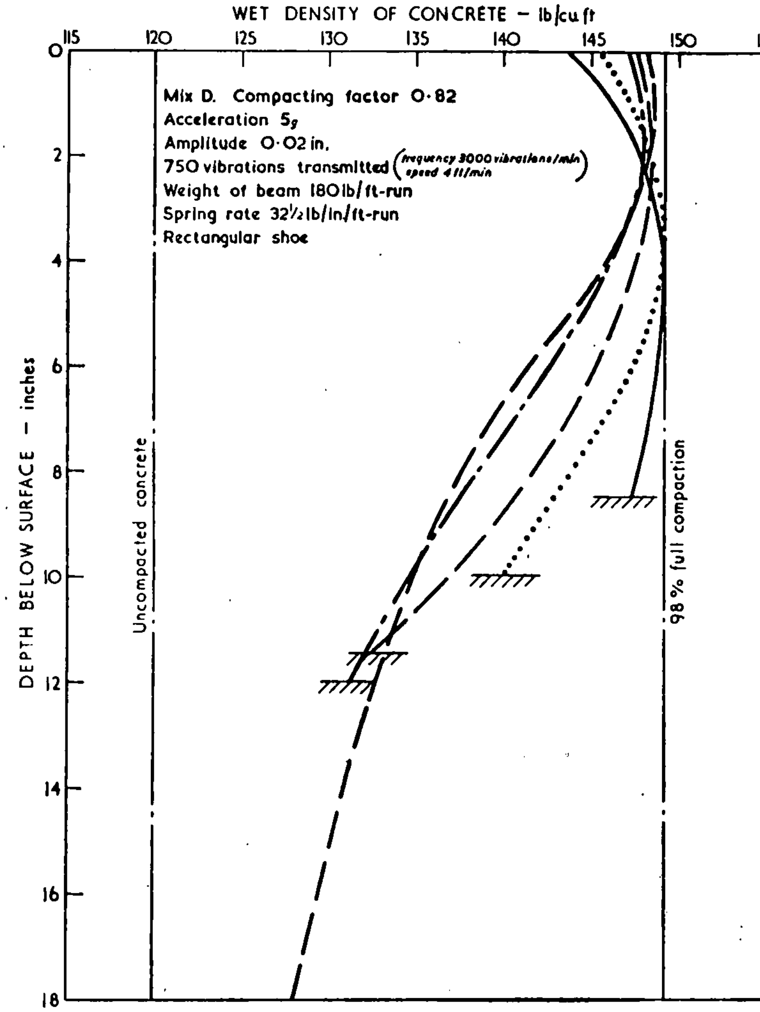
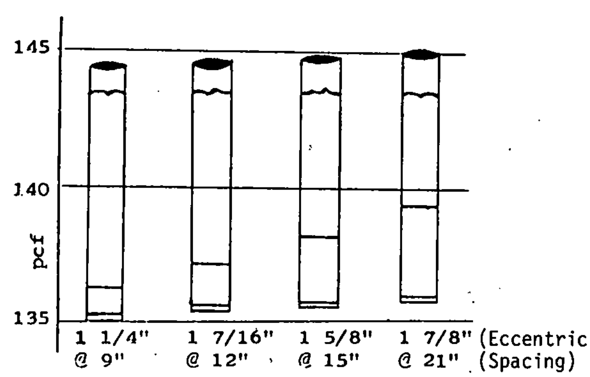


Figure 26. Effect of the thickness of the slab on the compaction of the concrete (20).



for I-270 Coarse Mix over Vibs. (Internal plus pan)

for I-270 Coarse Mix between Vibs. (Internal plus pan)

for I-80S Fine Mix over Vibs. (Internal only)

for I-80S Fine Mix between Vibs. (Internal only)

Figure 27. Variation of average density with amplitude of vibration for different eccentrics (42).

an adequate void system." This anomalous behavior is apparently explained by the fact that even though the volume of air is greatly reduced by the process of consolidation, the spacing factor, which is most significant in determining freeze-thaw resistance, remains adequate because the lower air contents are compensated for by the higher specific surface of the smaller voids that remain. Backstrom et al. (*26*) also reported that "with a given proportion of air entraining admixture, if other factors are held essentially constant, concrete develops a void system such that the spacing factor ($\bar{L}$) varies only slightly, regardless of the manipulation of the fresh concrete, within practical limits, and in spite of large changes in surface area and air content." As indicated in *TRB Special Report 119* (*60*), "Vibration has little effect on the smaller bubbles and, therefore, does not materially change the spacing factor, and such concrete would therefore have good durability in spite of a lower air content than is normally thought proper."

Tynes (*61*) has recently tested these hypotheses in the laboratory by subjecting adequately air-entrained specimens to extended vibration for periods up to 20 min. In some cases air contents were reduced from 8 to 2 percent. The spacing factor was not significantly changed. Although the resistance to freezing and thawing generally decreased with prolonged vibration, the spacing factor for the concrete from which the air had been removed was 0.0068 in. (0.17 mm); a spacing factor below 0.0080 in. (0.20 mm) is considered satisfactory (see section on "Loss of Air"). The lowest average durability factor (ASTM C 666) was 74 for concrete vibrated 20 min, whereas the corresponding durability factor for concrete vibrated 6 sec was 91 (a durability factor below 60 is considered unsatisfactory). Because high void contents reduce strength (about 5 percent for each percentage point of air content), this principle is important to the production of high-strength durable concrete.

Segregation

One of the most widely expressed concerns with vibration is the fear of segregation of the components of the mixture. Under the action of either internal or external vibration, the lighter components (water and cement paste) migrate upward; the denser coarse-aggregate particles move downward. This is evident in the extreme case shown in Figure 15. If vibration continues in a wet mixture, a zone of high water-cement-ratio paste or mortar accumulates at the surface or in the immediate location of the vibrator. The layer contains practically no coarse aggregate and may also have a frothy appearance. This zone is weak, porous, and of low durability. This condition is to be avoided; most specifications express various admonitions to limit its occurrence.

In the field research projects, observations of segregation were made in several ways, including visual observations, determination of gradings for aggregates extracted from the concrete, and measurements on hardened cores. No visual evidence of segregation or of significant variation in aggregate gradings related to vibration were reported in Mississippi, Texas, or Colorado. Illinois noted a very slight tendency toward segregation when the vibrator force $\left(\frac{w}{g} r\omega^2\right)$ approached 1,050 lb (4 670 N) (see Column 6, Table 2). ACI Committee 309 states that segregation can occur because of careless operation, a faulty mixture, or grossly oversized equipment. If segregation occurs, it is predominantly associated with overly wet mixtures or large differences of specific gravity between the coarse aggregate and the mortar. Accumulation of foamy laitance likewise indicates an improperly proportioned or overly wet mixture. Segregation was not found in any of the field projects. Slumps were predominantly 2 in. (50 mm) or less, and equipment met recognized standards.

Loss of Air

Consolidation, by definition, involves loss of air voids; however, the goal is that the loss be confined to the removal of the larger entrapped voids that are not needed for frost resistance. Most recent field research projects have included as a variable loss of air as a function of vibration. In most cases the comparison was made using measurements on the fresh concrete before and after vibration.

Illinois compared the air content before vibration with that obtained using the high-pressure method (*2*) on cores removed from the pavement. These comparisons showed a reduction of about 1½ percentage points of air within the range of 5 to 7 percent. A slight tendency to greater loss with increased vibrator force was also noted. On the basis of tests on fresh concrete before and after vibration, Mississippi found decreases in two-thirds of the samples; in the remaining cases the void content increased or did not change. The range of air contents was comparatively low (2 to 5 percent). Utah reported a loss of about 30 percent for a range of about 4 to 6 percent air. As shown in Figure 23, studies in Virginia measured on hardened concrete indicated a reduction of void content of about 40 percent for the range of 5 to 9 percent total void content. The void content was a function of the consolidation effort.

Backstrom et al. (*26*) likewise found a significant reduction in air content as a function of vibration time as shown in Figure 28. On the other hand, they found that the specific surface (α), which becomes larger as the bubbles become smaller, increased with vibration time, indicating that the bubbles remaining were smaller. Although the voids of all sizes were reduced, the proportion of voids less than 40 μm (1.57×10^{-6} in.) decreased from 83 to 82 percent of the original voids in the concrete. Voids greater than 60 μm (2.36×10^{-6} in.), which constituted the greater proportion of the air content of the concrete (vibrated 2 sec), were greatly reduced in frequency by the additional vibration. Spacing factor ($\bar{L}$)* is a good over-all measure of potential resistance to freezing and thawing; concrete with values less than approximately 0.008 in. (0.2 mm) generally has good frost resistance. As seen in Figure 28, for the insufficiently air-entrained specimen, the spacing factor was reduced with increased vibration; for the two

* Spacing factor: maximum distance of any point in the cement paste from the periphery of an air void.

adequately air-entrained specimens, the spacing factor increased slightly.

Unfortunately, none of the recently reported research studies measured the void parameters in hardened concrete under conditions that permit comparisons with the Backstrom data. ACI recommends that if the air content of the surface as measured by an air indicator decreases by more than 25 percent during vibration, changes should be made in the vibration procedures or the amount or type of air-entraining agent.

From the results reported, there is no doubt that vibration is expected to remove 25 to 40 percent of the total volume of air voids. Other experimental evidence suggests that this removal may be beneficial to strength and abrasion resistance without reducing freeze-thaw resistance because the total volume of entrained air is not necessarily the determinant of freeze-thaw resistance.

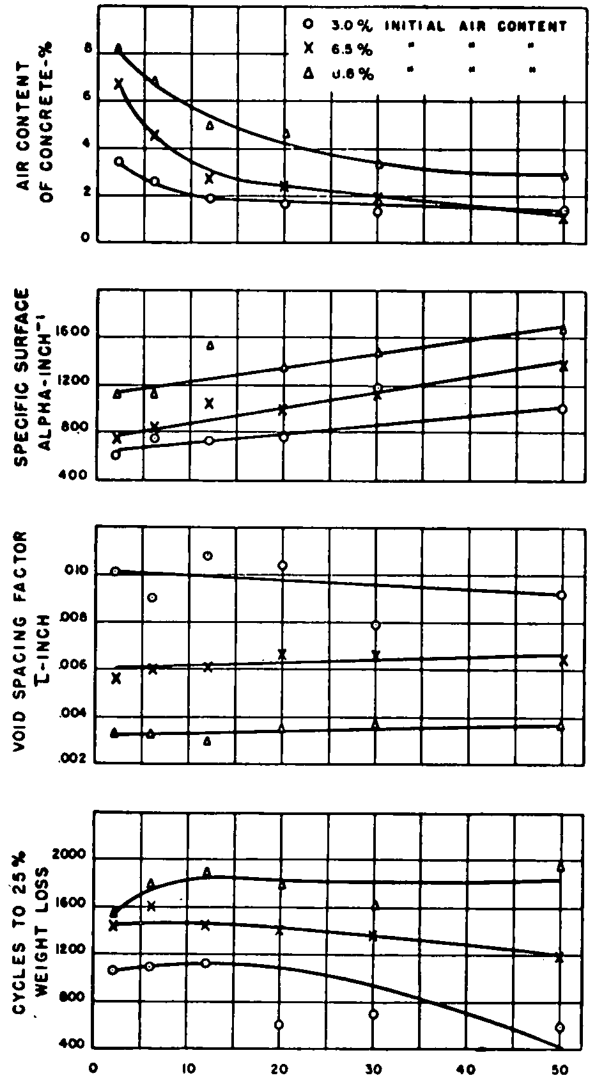


Figure 28. Effect of vibration on parameters of void system and freeze-thaw resistance (26).

Test Methods and Procedures

Two types of testing equipment and procedures are of interest in judging the adequacy of consolidation by mechanical vibration: those for checking the performance of the vibrating equipment and those for measuring the density of concrete before, during, and after vibration.

Vibration Equipment Tests

Vibratory units should be checked prior to the start of work and periodically during construction to verify that they are working as specified. The vibrating reed tachometer shown in Figure 29 is a simple device for checking the frequency of internal vibrators. The tachometer can be used to determine the frequency of the vibrator in air; in addition, by holding the device against the back end of the vibrator when nearly submerged, the frequency in concrete can be estimated. A more accurate value of frequency can be obtained by using a resonant reed tachometer, which is more expensive than the vibrating reed form. Both types of tachometers also can be used to determine frequency of external or surface vibrators.

The amplitude of an internal vibrator varies linearly along the head. The approximate average amplitude of most internal vibrators in air can be calculated as described previously. The maximum amplitude occurs at the tip of the vibrator. The amplitude can be measured using a visual effect scale (optical wedge) as shown in Figure 30. Scales printed on stickers can be readily attached to the vibrator head. When the head vibrates, a black triangle such as that shown in Figure 30 forms. The scale reading at the tip of the black triangle is the amplitude (half the total displacement) at this point on the vibrator.

These instruments are designed for field use and are more thoroughly discussed by ACI Committee 309 (*1*). For research purposes more sophisticated instruments (such as accelerometers) are available and have been discussed in some detail by Olateju (*50*).

Concrete Density Tests

Because most of the properties of concrete related to consolidation vary with density, the primary test methods of interest are those that permit measurement of this property. Traditional methods include the determination of unit weight of fresh concrete (ASTM C 138, AASHTO T 121) and the specific gravity and density of cores or other specimens taken from hardened concrete (ASTM C 642). Both of these methods are susceptible to relatively large variations. The determination of unit weight of freshly mixed concrete is based on a comparatively large sample but requires careful sampling and weighing. Measurements on cores involve a relatively small sample, 0.07 ft^3 (0.002 m^3), so any errors are magnified when converted to larger volumes. Considerable attention has been directed toward evaluation of the effectiveness of consolidation by comparing the density measured on cores taken from hardened concrete with that achieved on tests of fresh concrete or with the theoretical density calculated from the proportions and specific gravities of the components of the mixture.

The value of unit weight determined for the freshly mixed concrete obviously depends on the amount of compactive effort used. Traditionally, this test and most others are made with three layers, each of which is hand rodded with a standard metal rod. This compactive effort has been satisfactory for concretes with slumps greater than 3 in. (75 mm). Recently, most methods have been modified to require a standard mechanical vibration effort for concretes with slumps less than 1 in. (25 mm) with the option for either vibrating or hand rodding when the slump is between 1 and 3 in., the range of most interest for paving concrete. Hand rodding is suggested for slumps greater than 3 in. Marshall (*48*) reported a study in Washington to evaluate the relative influence of specimen compaction and specimen size and correlation between measurements made on freshly mixed and hardened paving concrete. No significant difference was found between the use of containers of either ½ or 1 ft^3 (0.014 or 0.028 m^3) for determining the unit weight of freshly mixed concrete. The smallest testing variance in the unit-weight test was found for consolidation by vibration. For the ½-ft^3 measure, the average unit weight for 19 samples was 150.24 lb/ft^3 (2 406.6 kg/m^3) for vibrated samples and 148.84 lb/ft^3 (2 384.3 kg/m^3) for hand-rodded samples. The average density of cores removed from pavements was 100.1 percent of the hand-rodded or 98.9 percent of the vibrated wet density. A specification was recommended on the basis of these results, which stated that to provide adequate density in the pavement, the density of an individual core of hardened concrete should be not less than 97.5 percent of the (vibrated) unit weight freshly mixed; in addition, the average density of three or more cores selected randomly from the pavement should be not less than 98.0 percent of the unit weight freshly mixed.

On the basis of its studies, Colorado suggested that cores have a relative density greater than 97 percent of the laboratory-rodded value, a somewhat lower requirement than that suggested in the Washington study.

As is the case with most tests of hardened concrete, the

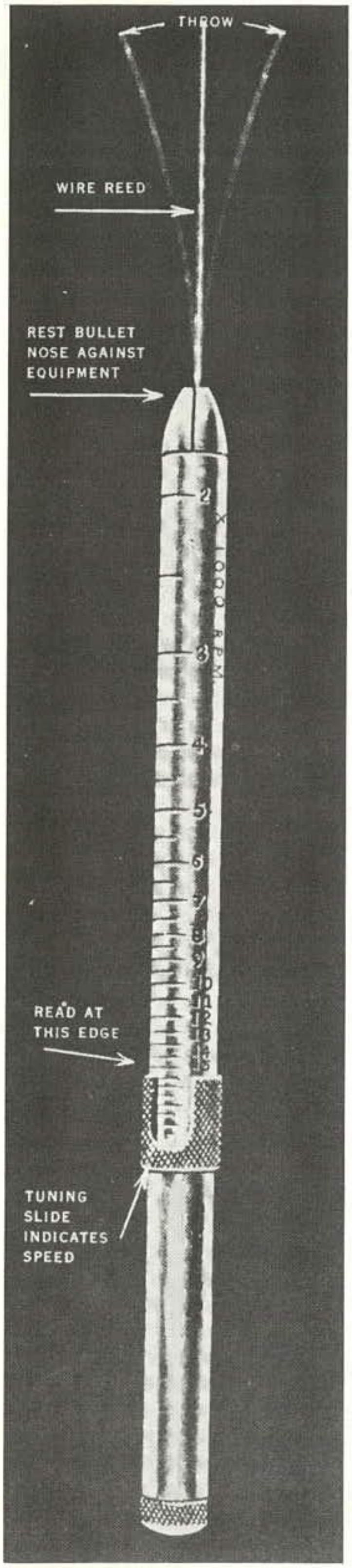


Figure 29. Vibrating reed tachometer (1).

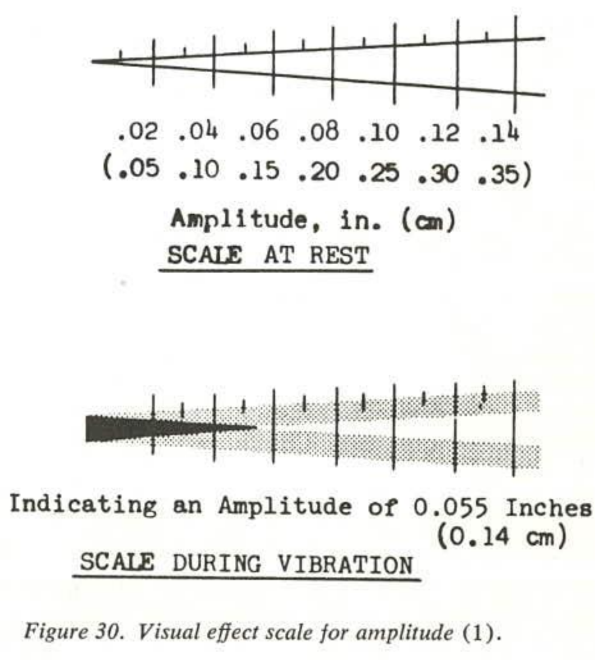


Figure 30. Visual effect scale for amplitude (1).

delay between placement and time of testing is undesirable because considerable quantities of concrete can be placed in the interim. Although accepted statistical principles are available for use in this situation, there is an obvious need for a rapid and nondestructive method for measuring density that permits rapid adjustments and corrections of equipment, procedures, or mixtures.

Most efforts have been directed toward adopting the nuclear methods widely used in measurement of density in soils, granular bases, and bituminous concrete mixtures (*62*). These methods involve measurement of the attenuation of gamma rays along the path between a radioactive source and detectors. This attenuation is significantly related to the density of the material. There are two methods that can be used in nuclear density testing—the direct transmission method and the backscatter method. In the direct transmission method, the radioactive source is submerged in the material and the sensor records the gamma rays reaching the surface. In the backscatter method, both the source and sensor are placed at separate places on the surface and the gamma rays that are reflected or scattered back are detected.

For the most part, nuclear methods are applied to intermittent measurements (i.e., the equipment is left in place for a given period during which the gamma rays reaching the detector are counted). The count rate can be appropriately correlated with density. This approach has been used for control of embankment compaction for more than 15 years, but until comparatively recently the application of this equipment to portland cement concrete had not been developed.

Studies by FHWA (*63*), Mississippi (*47*), and Colorado (*42*) have reported encouraging results for density measurements by direct transmission on fresh concrete when compared to other methods for measuring density. Teng (*47*) measured densities at transmission depths of 2 in. (50 mm) and 6 in. (150 mm) and found readings within ± 2.5 lb/ft^3 (± 40.0 kg/m^3) of conventional unit-weight tests. Four nuclear measurements were made at each location. The standard deviation was 1.13 lb/ft^3 (18.1 kg/m^3). Colorado used nuclear gauges and reported average nuclear readings 0.37 lb/ft^3 (5.9 kg/m^3) lighter than the average of measurements made on all other types of specimens. For one project the standard deviation was 1.45 lb/ft^3 (23.2 kg/m^3), and for the second project the standard deviation was 1.34 lb/ft^3 (21.5 kg/m^3). Clear and Hay (*63*) reported that densities of 99 percent ± 1 percent of rodded unit weight are possible with the technique. When slumps are greater than approximately 3 in. (75 mm), some difficulties have been encountered because of surface water seeping into the gauge. The presence of reinforcement also influences the results obtained (*64*).

The backscatter technique has not been extensively applied to measurements on freshly mixed concrete. The technique is limited to obtaining data from only the upper several inches; the depth to which densities can be measured by direct transmission depends on the depth to which the source can be inserted. Olateju (*50*) presented data obtained with the backscatter technique but no comparisons with other methods were given. Lepper and Rodgers (*65*) reported uncertainties in the area of 2 to 3 lb/ft^3 (32 to 48 kg/m^3). Both Colorado and Mississippi reported that in the direct transmission mode the nuclear device was able to provide density values 3 to 5 min after laydown. Limited measurements of density of hardened concrete by nuclear methods have also been made in Nebraska, North Carolina, and elsewhere (*62*).

Although nuclear gauges recently have received major attention for rapid density measurements, other methods have been explored, including electrical, sonic and ultrasonic, and acoustical. Deno and Monfore (*66*) showed that electrical resistance decreased with increasing amounts of vibration. Sonic methods (pulse velocity techniques) have been widely used for evaluating the properties of hardened concrete and have been standardized (ASTM C 597) for location of flaws and other defects (*67*). Field use of the technique with freshly mixed concrete has not been promoted because the very large attenuation of the sonic waves demands large and relatively nonportable equipment. Some preliminary trials have been made in Virginia using acoustical pulses (*68*). Results indicate that the pulses do change, as expected, with increased compaction. More development and evaluation of the technique are needed.

Nuclear gauges are widely used by transportation agencies for controlling density of embankments and of asphaltic concrete. This could be a useful method of measurements of density on both freshly mixed and hardened concrete. Further development of equipment and techniques specifically applicable to portland cement concrete is necessary. Although the results from intermittent measurements are available within 3 to 5 min, the need exists for "instantaneous" and continuous measuring techniques. A research contract has been awarded by FHWA for exploration and development of this type of instrumentation (*62*). The results to date are encouraging.

SUMMARY OF CURRENT PRACTICES

In 1972 the Highway Research Board Committee A2F01, Rigid Pavement Construction, prepared three separate questionnaires requesting information and opinions relating to the consolidation of pavements by vibration. These questionnaires were sent to specifying agencies, to paving contractors, and to equipment manufacturers in the United States. Details of current requirements on procedures and equipment and of any problems with consolidation were solicited from specifying agencies. Contractors were queried on their experience, practices, and equipment; equipment manufacturers were asked for opinions and recommendations for equipment and practices.

Replies were received from specifying agencies of 50 states and the District of Columbia. Forty-five paving contractors and several equipment manufacturers also furnished information. The responses have not been published or widely circulated outside of the TRB Committee. The questionnaires for each of the three groups are included in the Appendix. Following each question is a summary of the responses to that question. Specific responses of specifying agencies are given in Table 5. The following summary was made by Committee A2F01 after careful study of the responses to the questionnaires.

Specifying Agencies

- About two-thirds of the states allow the use of surface pan, spud, and tube vibrators. Only about one-fourth of the states require the use of any one type, although the spud is the most popular required type. The states differ on the combinations used; most leave great discretion to the engineer.
- More than half of the agencies do not specify maximum spacing of internal vibrators (*27*). Five specify 30 in. (760 mm), 7 require 24 in. (600 mm), and 3 require 18 in. (450 mm).
- Specified internal vibration frequencies range between minimums of 3,500 and 10,800 vpm. It is not clear whether these values refer to frequencies in air or under load in concrete. Eighteen states use 7,000 vpm as set forth in the AASHTO guide specifications.
- Amplitude requirements are generally not specified in positive terms. There is a distinct lack of information on amplitude.
- Normally, neither horizontal nor angular positioning of internal vibrators is specified. Reference is usually made to "full-width" vibration; however, specific guidance is often given as to the need for additional vibration near edge forms.
- No state currently specifies the size of internal vibrators.
- The forward speed of the paver is not specified by most states, although a few recognize the need for some control. Six states specify controls to prevent vibrators from running when the paver is stopped.
- Twenty-three states believe that excessive vibration definitely causes problems by bringing excess mortar or lightweight particles to the surface. Segregation is also noted as a problem, particularly when a large maximum-size aggregate is used. The fact that this segregation is strongly associated with high-slump concrete does not seem to have been recognized in the responses.
- Several states report problems at construction joints, particularly in continuously reinforced concrete-pavement construction, and other critical locations. Some states require additional hand vibration at these locations.
- A majority of the states do not consider fluctuation of air content to be a major problem if vibration is "performed properly." A few states report losses up to 1.5 percentage points of air (about 25 percent of the total void volume).
- Minimum frequency specified for surface pan vibrators ranges between 3,500 and 4,000 vpm with 3,500 vpm indicated as the most commonly used. This value also reflects that suggested in the AASHTO guide specifications. Fifteen states either do not specify or did not reply to the question concerning this type of vibrator.
- Specified ranges of minimum frequency from 3,500 to 7,000 vpm are reported for tube vibrators. The most common minimum frequency is 5,000 vpm, which is the frequency suggested in the AASHTO guide specifications. Sixteen states do not specify or did not reply to the question concerning this type of vibrator.
- Most states do not express concern about the need for maximum frequency for vibrators. One state specifies 10,000 vpm as a maximum for pan or tube vibrators.
- Twenty states make reference to instruments for checking vibrator frequency; thirty states do not. There is no indication as to the extent to which these checks are actually made.
- Only fourteen states report that the adequacy of vibration is checked at the beginning of the work. Eighteen states report checking by visual observation or cores. Sixteen do not provide for any checking or did not reply.

Contractors

- About one-third of the contractors change vibrators from project to project for a variety of reasons, including (a) change in mix design, (b) different state specifications, (c) different engineer preference, (d) different type of pavement, (e) change in pavement thickness, and (f) higher production rate.
- About one-half of the contractors adjust vibration after beginning paving operations on a given job for reasons such as (a) adjustments in elevation due to steel and extension plate, (b) changes to fit changes in slump, and (c) engineer's preference.
- Replies from four of the forty-five contractors indicate that they change frequency and horizontal position with changes of forward speed of the equipment. Those that make changes vary (a) generator speed or (b) number and/or spacing of vibrators.
- About one-half of the contractors believe that variation of paver speed without vibrator adjustment has a significant effect on consolidation.
- A variety of potential problems are attributed to vibration, although many contractors do not list any problems. Problems listed include:
  - —Drifting of concrete on curves because of superelevation.
  - —Tendency of mortar to follow track with slight depression.
  - —Insufficient vibration at construction joints.
  - —Movement of steel.
  - —Irregularities of contact with dowel baskets.
  - —Overrun of quantities.
  - —Inadequate vibration under steel.
  - —Problems causing speed of paver to be critical.
  - —"Frothing," particularly with some aggregates.
- Responses indicate considerable variation of distance of vibrators to edge for slip-form paving. Distances vary from 2 to 4 in. (50 to 100 mm) to 15 in. (380 mm), with 10 to 12 in. (250 to 300 mm) most commonly used.
- Spud vibrators are used by most contractors, although most of the same contractors have some experience with pan and/or tube vibrators.
- Experience with spuds includes:
  - —Good results with harsh mixtures.
  - —Can be used on form and slip-form paving.

TABLE 5

RESPONSES OF SPECIFYING AGENCIES TO TRB RIGID PAVEMENT CONSTRUCTION QUESTIONNAIRE

STATE	1. Type of Vibration Used										2. Internal Vibration, Specifications For									
	Surface Pan		Spud		Tube		All		Other		Spacing	Frequency	Amplitude	Horizontal Position in Pavement (In.)					Ang. Position in Long. Plane	Fwd Spec. of Equip. F.P.M.
	*R	*A	R	A	R	A	R	A	R	A	(In.)	V.P.M.		7	8	9	10	Other		
ALABAMA								X				5000								2(8)
ALASKA																				
ARIZONA		X	X								24	3500							+10°	
ARKANSAS								X		X	24	3500						2(3)		
CALIFORNIA	1(2)		1(2)								30	5000	2(2)							
COLORADO	X		X			X						7000						2(10)		
CONNECTICUT			1(6)									3500								
DELAWARE			1(6)					X												
FLORIDA								X				3500								
GEORGIA								X				7000								
HAWAII								X				7000								
IDAHO	X			X	X						24	10800							2(4)	
ILLINOIS		X		X							24	7000								
INDIANA								X			24	7000								
IOWA				X		X				X		3500/7000						2(3)		2
KANSAS							X				18	7000						2(10)		
KENTUCKY								X				3600								
LOUISIANA		X	X			1(3)					18	5300						2(2)	45°-90°	6
MAINE		X						X				3500/7000	2(9)							
MARYLAND			1(1)					X			30	5000	2(2)	3.5	3.5	3.5	3.5		0°	
MASSACHUSETTS								X				3500/7500								
MICHIGAN	1(1)			X																
MINNESOTA		X		X								3600/6000								
MISSISSIPPI								X				7000								
MISSOURI								X				4500								
MONTANA								X				7000								
NEBRASKA								X				4000								2(5)
NEVADA		X			X						30	5000	2(2)					2(10)		
NEW HAMPSHIRE																				
NEW JERSEY									1(5)			5000				2(10)			90°	2(5)
NEW MEXICO		X	X			X		X			30	7000								
NEW YORK	X		1(5)			X				1(4)	18	5000/7000								
NORTH CAROLINA								X												
NORTH DAKOTA							X					5000/7000								
OHIO				X		X				1(4)	24	5000/7000								
OKLAHOMA								X				7000								
OREGON								X				3500								2(5)
PENNSYLVANIA								X				6000								
RHODE ISLAND								X												
SOUTH CAROLINA								X				5000/7000								
SOUTH DAKOTA								X				7000								
TENNESSEE		X		X						1(7)	2(1)	2(1)	2(1)	2(1)	2(1)	2(1)	2(1)		2(1)	2(9)
TEXAS			X					X			24	5000/8000								2(8)
UTAH				X		X														
VERMONT																				
VIRGINIA				X								3500/7000								2(7)
WASHINGTON	X			X		X					18	5000	2(2)	2(4)	2(4)	2(4)	2(4)			2(6)
WEST VIRGINIA								X				5000/10000								
WISCONSIN		X		X								7000								
WYOMING								X			30	7000								
DIST. OF COL.																				

TABLE 5 (*continued*)

STATE	3. Problems Resulting from Vibration: Surface	Segregation	Rainforcing Joints	Entrained Air	Other	Int.Vibr. Prob.Specifically	4. Frequency and Amplitude Requirements: Frequency (V.P.M.) Surface Pan	Frequency (V.P.M.) Tube	Limits On Use: Yes	Limits On Use: No	5. Testing Devices Req. for Vibrs.: Tachometer Yes	Tachometer No	Other Yes	Other No	6. Adeq. of Vibration Checked: Start of Work Yes	Start of Work No	Other Times Yes	Other Times No
ALABAMA		3(4)	3(14)		3(22)		3500	7000		X		X		X		X	6(1)	
ALASKA																		
ARIZONA	3(1)			3(17)			3500			X		X		X	X			
ARKANSAS	3(1)	3(4)	3(14)					3500		X		X		X			X	
CALIFORNIA	3(1)			3(1)			3500	5000	X		X		X		X		X	
COLORADO	3(1a)	3(7)		3(17)		3(23)	3500	5000	4(3)			5(3)			X		X	
CONNECTICUT										X								
DELAWARE										X							6(1)	
FLORIDA			3(14)			3(14)	3500			X	X			X			6(1)	
GEORGIA				3(16)			3500	5000	4(4)		X			X	6(2)			
HAWAII							3500	5000		X	X			X		X		X
IDAHO	3(1)	3(6)		3(18)			3500			X	X			X	X			X
ILLINOIS	3(1)		3(8)		3(20)		3500		4(9)		X			X		X	6(1)	
INDIANA	3(1)		3(9)	3(15)			3500	5000		X		X		X	6(1)			
IOWA	3(2)										X		X		X		X	
KANSAS		3(5)			3(17)	3(5)	3500	5000	4(4)		X			X		X	6(1)	
KENTUCKY							3600	3600		X		X		X			6(1)	
LOUISIANA	3(1)	3(6)	3(8)					5300	4(7)		X		X		X		X	
MAINE	3(1)			3(19)			3500	5000	4(5)			X		X	6(1)		6(1)	
MARYLAND	3(1)(1a)		3(8)	3(17)					4(1)(16)		X		X				6(1)	
MASSACHUSETTS							3500	5000	4(10)			X		X		X		
MICHIGAN	3(1)		3(10)	3(16)			3600		4(8)			X		X			6(1)	
MINNESOTA	3(2)	3(4)		3(15)			3000/6000			X	X			X			6(1)	
MISSISSIPPI						3(24)	3500	5000		X		5(2)		X	X		X	
MISSOURI			3(13)				3600	4500		X	X		X		6(1)		X	
MONTANA							3500	5000		X		X		X	6(1)		6(1)	
NEBRASKA					3(22)		4000	4000	4(17)		X		X			X		X
NEVADA								5000			X	X			X	X		
NEW HAMPSHIRE																		
NEW JERSEY	3(1)	3(4)	3(11)			All						X		X			6(1)	
NEW MEXICO	3(1a)	3(1)		3(17)			3500	5000	4(6)		X		X			X		X
NEW YORK	3(1)	3(4)	3(11)		3(22)	All	4000		4(18)			X		X	6(1)		6(1)	
NORTH CAROLINA	3(1)		3(13)			3(13)	3500	5000	3(13)	X			X			X		X
NORTH DAKOTA	3(1)		3(12)	3(18)		3(1)	3500	5000	4(13)			X		X		X	X	
OHIO			3(10)					5000	4(11)			X		X		X		X
OKLAHOMA		3(4)					3500	5000		X		X		X		X	6(1)	
OREGON	3(3)	3(4)	3(8)	3(18)	3(20)	All		3500		X	X		X		X		X	
PENNSYLVANIA		3(4)	3(10)				4(2)	4(2)	4(4)		X	X	X		X		X	
RHODE ISLAND												X		X		X		X
SOUTH CAROLINA							3500	3500		X		X		X		X		
SOUTH DAKOTA			3(8)				3500	3500		X	X	X	X			X		
TENNESSEE							4(1)	4(1)	4(15)			X		X	6(1)		6(1)	
TEXAS	3(1)	3(4)	3(8)				3500/4200	5000	4(14)	X	X			X		X	6(1)	
UTAH	3(1)(1a)	3(4)	3(8)	3(18)						X		X		X	X		X	
VERMONT																		
VIRGINIA		3(4)			3(24)							X		X		X		X
WASHINGTON	3(1)	3(4)		3(18)		3(1)		5000	4(12)		X			X	X		X	
WEST VIRGINIA	3(1)	3(4)	3(14)				3500	5000	X									
WISCONSIN						3(23)	3500			X	5(1)		5(1)			X		X
WYOMING							3500	5000		X		X		X	X		X	
DIST. OF COL.																		

STATE	7. Testing Equipment Needed			8. Field or Laboratory Research Conducted		Findings Reported	
	Yes	No	Type	Yes	No	Yes	No
ALABAMA			Unknown	X		8(8)	
ALASKA							
ARIZONA	X		Plastic Concrete Density Device		X		X
ARKANSAS			Unknown		X		X
CALIFORNIA	X		Tachometer or Vibration Meter	X		8(9)	
COLORADO	X		Direct Transmission Nuclear Gage	X		8(1)	
CONNECTICUT							
DELAWARE							
FLORIDA				X		8(5)	
GEORGIA	X		Tachometer				
HAWAII					X		X
IDAHO	X		Nondestructive Test for Consolidation		X		X
ILLINOIS		X		8(2)			
INDIANA	X		Portable Core Drill	8(2)			
IOWA	X		Vibra-Tak		X		X
KANSAS	X		Coredrill.Lin.Trav.Mach.Lap.Mach&Conc.saw			8(3)	
KENTUCKY		X			X		X
LOUISIANA	X		Vibra-Tak & Amplitude meter		X		X
MAINE		X			X		X
MARYLAND	X		As recommanded by manufacturer		X		X
MASSACHUSETTS					X		X
MICHIGAN	X		Plastic Concrete Density Device		X		X
MINNESOTA	X		Fowler Vibra-Tak		X		X
MISSISSIPPI		X		X		8(4)	
MISSOURI	X		Coredrill & Tachometer		X		X
MONTANA	X		Not specified or unknown		X		X
NEBRASKA	Unknown				X		X
NEVADA	X		Tachometer		X		X
NEW HAMPSHIRE							
NEW JERSEY	X		Nondestructive Test for Consolidation		X		X
NEW MEXICO	X		Plastic Concrete Density Device		X		X
NEW YORK	X		Tackometer,Amp. Meter & Fl. Press Mixer	X		8(2)	
NORTH CAROLINA	X		Vibra-Tak		X		X
NORTH DAKOTA	X		Plastic Concrete Density Device		X		X
OHIO		X			X		X
OKLAHOMA		X			X		X
OREGON	X		Coredrill	X			X
PENNSYLVANIA			Unknown		X		X
RHODE ISLAND		X			X		X
SOUTH CAROLINA		X			X		X
SOUTH DAKOTA		X			X		X
TENNESSEE		X			X		
TEXAS	X		Coredrill	X		8(7)	
UTAH		X		X		8(2)	
VERMONT							
VIRGINIA		X		X		8(10)	
WASHINGTON	X		Plastic Concrete Density Device & Coring	X		8(10)	
WEST VIRGINIA							
WISCONSIN			Unknown	X		8(5)(6)	
WYOMING			Unknown		X		X
DIST. OF COL.							

TABLE 5 (*continued*)

STATE	9. Comments
ALABAMA	
ALASKA	No rigid pavement used in State due to subgrade deformation.
ARIZONA	Should specify ft-lb of energy/unit volume of concrete.
ARKANSAS	
CALIFORNIA	
COLORADO	Contemplate use of 97% rodded density as specif. req. This was developed from field research using nuclear gages.
CONNECTICUT	
DELAWARE	
FLORIDA	
GEORGIA	
HAWAII	
IDAHO	Interested in void or density correlation by Nuclear Densometer.
ILLINOIS	Eccentric size has strongest influence on concrete properties and paver speed the weakest.
INDIANA	Need information on accurate to measure vibratory energy in plastic concrete.
IOWA	Vibrator Manf. should adopt a standard rating system taking into account the wt. and swing of eccentric, etc.
KANSAS	Vibration does no harm to air content and removes most large air entrapments. Does not remove excess water.
KENTUCKY	
LOUISIANA	Adequate consolidation of concrete mixes must be by observation and previous experience.
MAINE	
MARYLAND	Slump control is very important.
MASSACHUSETTS	
MICHIGAN	
MINNESOTA	Keeping vibration below 6000 vpm prevents shale segratation and pop outs.
MISSISSIPPI	
MISSOURI	Correlation needed between Amplitude and Frequency. Establish mx.& min. time of vibration at specified frequency.
MONTANA	Specification needs revising.
NEBRASKA	
NEVADA	All PCCP placed by slip form with no problems.
NEW HAMPSHIRE	No reply.
NEW JERSEY	
NEW MEXICO	More information needed on effects of vibration.
NEW YORK	
NORTH CAROLINA	We write specifications as end result.
NORTH DAKOTA	Vibration is vital and no problem if done properly. Proper inspection and operation is answer.
OHIO	Excess vibration at transverse steel on CRCP by slipform causes water to collect & flow to edge causing edge slump.
OKLAHOMA	
OREGON	Nuclear gages being used to determine consolidation and density.
PENNSYLVANIA	
RHODE ISLAND	
SOUTH CAROLINA	Try to consolidate adequately at CRCP construction joints.
SOUTH DAKOTA	
TENNESSEE	Tennessee does not place CRCP.
TEXAS	Tube type vibrator not presently being used in Texas.
UTAH	To get proper results research should be part of contract.
VERMONT	Vermont does not construct FCCP.
VIRGINIA	Spud vibrators give the best results when used properly.
WASHINGTON	Need to develop proper V.P.M./amplitude characteristics to produce consistent quality concrete pavement.
WEST VIRGINIA	
WISCONSIN	
WYOMING	Guidelines issued for determining adequacy of vibration. (See Dec. 1971 ACI Journal)
DIST. OF COL.	Wrong questionnaire returned.

10. Footnotes

First number in footnote designation indicates section in table and number in parenthesis indicates sequential number of footnote.

Three States plus the District of Columbia did not furnish comments for reasons noted in Comments, Item No. 9.

*R Required
*A Allowed
1(1) Required for CRCP only
1(2) Requires internal vibration at edges plus pan or full width internal vibration
1(3) Allows tube on 2-course construction along with spud vibrators
1(4) Vibrating mesh depressor or screeds
1(5) Spud used as only vibration at longitudinal and transverse joints
1(6) Internal at edges only
1(7) As permitted by the engineer

2(1) As recommended by manufacturer
2(2) Sufficient to be perceptible at surface
2(3) Depth of reinforcement determines placement
2(4) At midpoint
2(5) Speed geared to concrete production for continuous forward movement
2(6) Vibrating equipment matched to speed
2(7) Vibrator stopped when machine is stopped
2(8) Vibrator stopped if stop exceeds 15 seconds
2(9) Maximum 5 seconds vibration in one place
2(10) Within specified pavement thickness

3(1) Causes excess mortar on surface susceptible to wear
3(1a) Poor density and surface wear due to under vibration
3(2) Excessive vibration brings shale and coal to surface causing pop outs
3(3) Causes edge problems with slip form paving
3(4) Settlement or segregation of coarse aggregate by excess vibration
3(5) Water accumulates along steel mesh
3(6) Rapid travel of slip form pavers in stiff mixes caused segregation
3(7) No problem even with heavy vibration
3(8) Inadequate consolidation at CRCP construction noints (Hand vibration required at joints)
3(9) Lack of adequate consolidation causes concrete to slump between steel
3(10) Vibration causes surface dips at dowel joints, reinforcing steel, and mesh laps
3(11) Poor consolidation at keyed longitudinal and transverse joints
3(12) Concrete hangs up on reinforcing steel with lack of proper consolidation
3(13) Concrete not consolidated at steel and mesh laps
3(14) Displaces reinforcement or dowels
3(15) Minor loss of air with vibration
3(16) Up to 1-1/2% air loss
3(17) No loss with normal to heavy vibration
3(18) Reduced with excess vibration
3(19) Pan type causes loss of air at surface
3(20) CRCP failure appears to be caused by lack of vibration (isolated areas)
3(21) Edge slump and roughness may be effected by vibrarion
3(22) Displaces steel other than at joints
3(23) Internal vibration improves lower lavers more than surface
3(24) Poor consolidation due to lack of adequate internal vibration

4(1) Manufacturer's recommendation
4(2) Frequency necessary to consolidate concrete
4(3) Tube not effective
4(4) Automatic shutoff when equipment stopped
4(5) Surface pan not allowed on lower course of two course pavement
4(6) Slipform requires spud vibrators
4(7) 10,000 V.P.M. maximum for either type
4(8) Use of pan optional with engineer
4(9) Tube not allowed
4(10) Pan on top course only and not over trans. joints
4(11) Surface pan not allowed
4(12) Must produce 98% of rodded density
4(13) Position to miss steel in pavement
4(14) Surface pan for two lift construction and internal for full depth. Both types may be used concurrently as permitted by engineer
4(15) All types other than multiple spud must be approved by the engineer
4(16) Pan permitted on slipform if part of the machine
4(17) Surface pan not allowed on slip form
4(18) Minimum of 4-second immersion of internal type along forms and joints. Shut off when paver stopped

5(1) Rarely
5(2) Contemplating use
5(3) Not required but use it

6(1) Check by visual observation or cores
6(2) By 1000 ft. test section

8(1) 9000 V.P.M. + 1 7/8" diameter at 24" spacing provides adequate consolidation
8(2) Study now in progress
8(3) Useful air hard to remove - good bubble count and spacing even after gross over-vibration with total air down to 1%
8(4) Concrete with over 1" slump had higher density than minus 1" slump concrete
8(5) No segregation of course aggregate caused by vibration
8(6) Mesh position not disturbed
8(7) Uniform concrete obtained within following limits: (a) 8-12 F.P.M. paver speed, (b) 7000-9000 V.P.M., and (c) 8-12 vibrators per 24' width
8(8) See HPR Report No. 50 (Alabama)
8(9) High frequencies are beneficial
8(10) Inconclusive results

- Experience with pan vibrators includes:
  - —Good backup system for spuds.
  - —Honeycombing under steel.
  - —Aids finishing of surface.
- Experience with tube vibrators includes:
  - —Satisfactory with slip forming.
  - —Can overload finishing machine.
  - —Can be used for variable widths.
- Most contractors (about half) have excellent-to-good results with spud vibrators. Experience with pan and tube vibrators varies from excellent to poor.
- There is broad agreement on philosophy in contractors' recommendations to improve vibration results, which include:
  - —Automatic controls to vary vibration with slump and speed, including automatic shut-off.
  - —Discontinuance of use of pan and tube vibrator.
  - —Closer control of spacing.
- Most contractors do not have instruments on pavers to monitor vibrator frequency. Some use meters with satisfactory results.
- Half of the contractors use tachometers to some extent, but there is no agreement as to the desired frequency for checking with these instruments. There is also no agreement about whether the check should be made in air or in the concrete.

Manufacturers

- All manufacturers prefer spud vibrators either alone or in combination with other types. Two report surface pan or tube vibrators as acceptable, although one considers the surface pan to be unacceptable.
- There is general agreement that:
  - —The characteristics of the vibrator (frequency and eccentric size) must be matched with the mixture and conditions with particular attention to slump, aggregate size, and slab depth.
  - —Checks for adequacy of vibration should be made.
  - —Value of high-frequency vibration should be about 9,000 to 10,000 vpm.

CHAPTER FOUR

BRIDGE DECKS

Consolidation of concrete for bridge decks is similar to that for pavements. Construction of a bridge deck, however, differs from construction of pavements in important ways that are reflected in the type of concrete used and the methods of consolidation. Pavement construction involves continuous placements with highly specialized equipment designed to place up to 2 miles (3 km) per day, whereas bridge decks are individual elements usually requiring only 10 to 20 loads of ready-mixed concrete. Bridge decks are more heavily congested with reinforcement and thus require concrete with a somewhat higher slump and smaller maximum-size aggregate than is normally used in pavements. Although mechanical screeding and finishing are used on most bridge deck construction, these machines are not normally equipped with vibrators; the principal method for consolidation is the hand-held individual internal vibrator. The slab thickness and congestion of reinforcement generally preclude the use of surface vibrators.

Figure 31 shows the essential processes of bridge deck placement. Generally, concrete is placed in front of the mechanical screed, which may operate either parallel or perpendicular to the centerline of the roadway. The screeds may be vibrating but normally are not. The concrete is consolidated in front of the screed, which then brings the concrete to the intended profile. Of special note in Figure 31 are the spare vibrators in the foreground that are available for equipment breakdowns or for special areas. This is a required practice for quality bridge decks.

Concern for deterioration of bridge decks has prompted an extensive research effort to identify causes (*70*). The major causes of deterioration have been recognized as related to the properties of the concrete itself rather than to structural characteristics. A significant contributor to distress has been the extensive and increased use of deicing chemicals for snow removal.

The major defects that have been identified are damage from freezing and thawing, corrosion of reinforcement, and surface spalling over reinforcement (*71*). Each of these defects is accelerated by improper consolidation, the first two in ways that have already been discussed. Spalling over reinforcement is associated with corrosion, and there are some indications that the fracture planes that sometimes develop are influenced by sedimentation or settling that occurs in the concrete after placing and finishing. Attempts have been made to use delayed vibration or revibration to counteract the effects of this settling. Although much research has been directed toward premature deck deterioration, none has been specifically concerned with consolidation except a project to evaluate revibration that is discussed later. The major defects identified, however, are all mitigated by proper vibration because the important resisting properties are improved by low water-cement

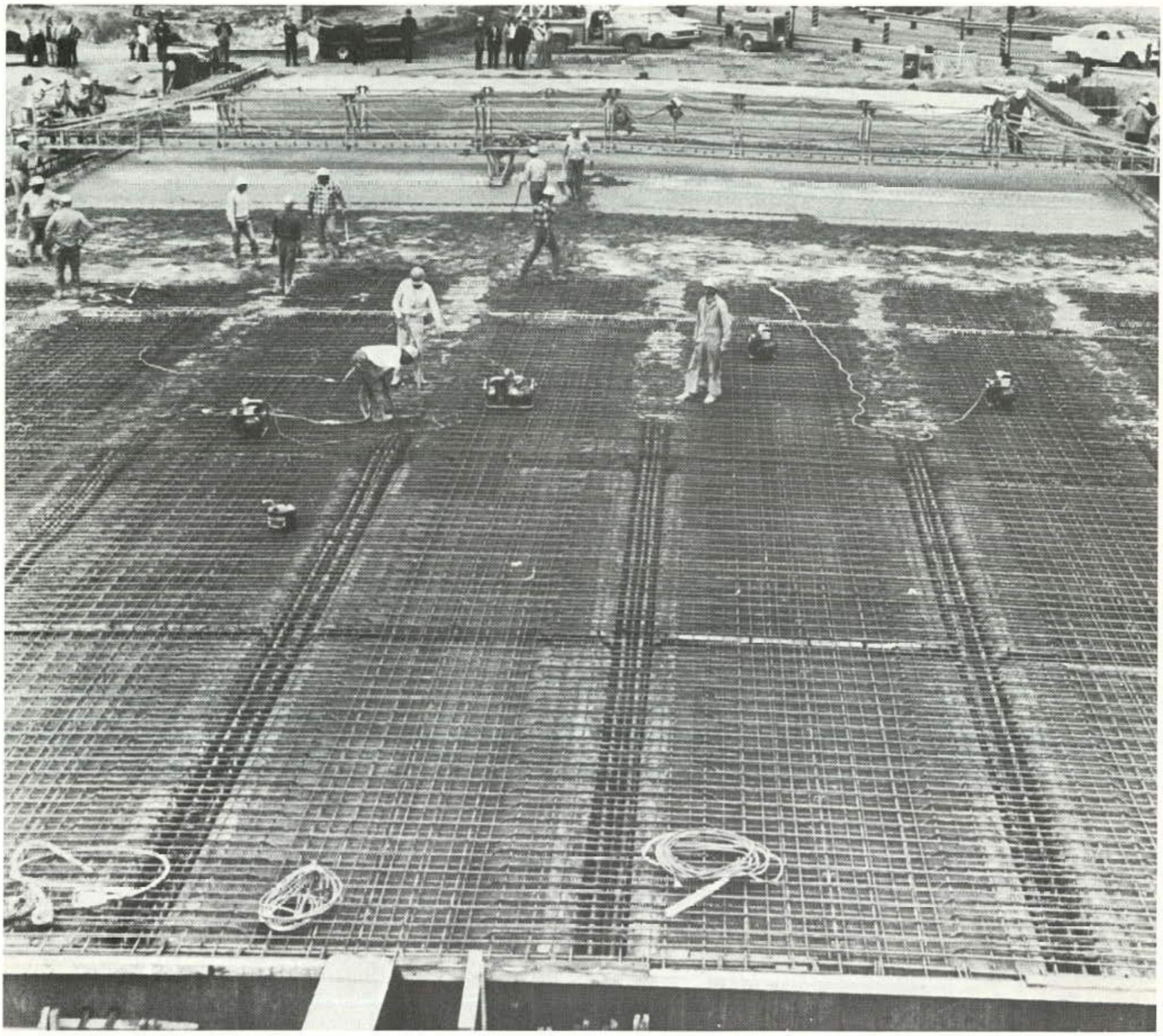


Figure 31. Bridge deck construction (69).

ratios and the lowest possible permeability. As shown in Figure 16, underconsolidation of deck concrete can be responsible for voids, particularly under the reinforcement. In this regard, an excerpt from the "Recommended Practice for Bridge Deck Construction" of ACI Committee 345 is instructive (*38*):

> Deck requirements differ in some respects in that concrete subsidence is restrained by closely spaced and chair-supported reinforcing steel and in that the head of concrete is low. In hot windy weather, surface crusting is a problem which tends to promote early finishing. This, in turn, forces vibration operations to be completed before the subsidence of the concrete due to bleeding is completed. There is concern sometimes that concrete will be "over-vibrated" or "over-finished." This more than likely implies that the concrete was of a consistency so wet that it should not have been vibrated at all or that the finishers were working on the drying surface crust an hour or more before bleeding and subsidence were completed.
>
> It is essential that bridge deck concrete be thoroughly vibrated at a time late enough to assure close contact with reinforcing steel after the concrete has ceased to subside. This may require revibration if bleeding is prolonged, and it generally occurs for a much longer time than is obvious. It may be necessary to use an evaporation inhibitor to delay the time the finishers start and still vibrate at a late enough time to get proper consolidation. Retarding admixtures may delay initial set time and permit later vibration but may not prevent surface crusting due to drying.

The potential benefits of revibration were recognized by Vollick (*72*) in studies reported in 1958. There has been a strong belief that surface spalling was related to subsidence that created planes of weakness at the level of the reinforcement and that this type of distress would be reduced by delayed vibration that would close any incipient fracture planes.

A research project, reported by Hilsdorf and Lott in

1970 (*73*), was conducted to evaluate revibration of bridge decks under both laboratory and field conditions. Responses from a survey of agencies with the United States and Canada indicated no known cases of intentional revibration of bridge decks. One case of delayed vibration was reported but the techniques were not generally used. The procedures employed in the laboratory trials used a surface vibrator with a frequency of 3,200 cpm, a forward speed of 7.5 fpm (2.3 m/min), and a calculated centrifugal force of 720 lb (3 200 N). In some cases, the force was reduced to 180 lb (800 N). These experiments showed that the high-energy-level vibration closed early-shrinkage cracks and improved moderate crusting. In all cases of moderate or severe crusting, extensive additional finishing after revibration was required. It was concluded that high-energy revibration could be conducted successfully until the penetration resistance reached a value of 60 psi (410 kPa), as determined in accordance with ASTM C 403. To verify the results from the laboratory tests, experiments were conducted in Illinois and Kansas with revibration on portions of three decks. On the first two decks difficulties were encountered with the equipment being used, and considerable finishing after revibration was required. For the third deck a new vibrating screed was constructed, and the experiment was generally successful. No report on the long-term benefits has been issued.

Clear and Hay (*63*) employed surface revibration on some slabs 4 ft by 5 ft by 6 in. (1.2 m by 1.5 m by 150 mm) that were part of their study of time-to-corrosion of reinforcement. They found a very slight but insignificant reduction of chloride content at the level of the reinforcing steel for those slabs as compared with those adequately vibrated internally. The revibration was applied when the penetration resistance of the concrete was 30 to 60 psi (210 to 410 kPa) (ASTM C 403). Thus, it appears that delayed vibration and revibration offer some promise; however, extensive development of equipment and procedures are needed.

No survey of current practice for consolidation of bridge decks has been performed. A review of selected specifications suggests that there is considerable variation in requirements. The minimum frequency specified is generally lower than that reflected in specifications for paving; a typical value is 4,500 vpm. There often is a note that the intensity of the vibration should be sufficient to affect visibly a mass of concrete having a 1-in. (25-mm) slump through a radius of 18 in. (450 mm). Comparison of this requirement with those stated in Table 2 would suggest that this value is larger than the radius of action associated with vibrators of the type available for use with bridge slabs (Groups 2 and 3). The frequency is also significantly lower than that suggested in Table 2. Few specifications indicate the number of vibrators necessary as a function of rate of placement, but again reference to Table 2 would suggest that 3 or 4 vibrators and an extra one as a backup would be required for a typical bridge deck with placement rates of 30 yd^3/hour (23 m^3/hour). Although placement rates vary, this rate is achievable as indicated in the recommendations by ACI Committee 345 (*38*).

Few published reports have been issued reflecting in-place density testing of freshly mixed concrete on bridge decks. Clear and Hay (*63*) used direct transmission to monitor the density of slabs used in their study of corrosion. When these density measurements indicated that the density was less than 99 percent ± 1 percent of laboratory rodded density, additional internal vibration was used to achieve the desired value. If such tests are to be made on actual construction, it is desirable to make them after consolidation but prior to passage of the screed so that corrections, if needed, can be made. The presence of large quantities of reinforcement near the surface also must be recognized and appropriate calculations made. Once the screed has passed, the profile has been established and it is very difficult and perhaps counterproductive to attempt additional consolidation.

CHAPTER FIVE

OVERLAYS, SPECIALIZED MATERIALS, AND SPECIAL PROCESSES

Overlays are used on both pavements and bridge decks for rehabilitation of surfaces or to impart special properties to surfaces of new construction. Overlays are built over existing concrete surfaces, bituminous pavements with flexible bases, or old concrete pavements that have already had one or more bituminous overlays. Overlays may be bonded, partially bonded, or unbonded. Thicknesses of overlays may vary from as small as ½ in. (12 mm) on bridge decks to 8 in. (200 mm) or more for heavy-duty pavements. Overlays may be unreinforced, lightly reinforced, or continuously reinforced.

Proper consolidation of overlays is particularly important. In addition to improving the properties of the overlay material, proper consolidation improves the bond of the overlay to the base surface. When the overlay is greater than approximately 4 in. (100 mm) thick, which is the case for most pavement overlays, consolidation methods differ little from those already discussed. When thinner overlays are used, however, several considerations arise that merit special mention.

By definition, thin overlays preclude the use of large immersion vibrators because immersion vibrators must be operated completely submerged. Thus, surface vibrators are usually used to consolidate overlays, although small immersion vibrators may be used on overlays with thicknesses of 3 in. (75 mm) or greater. In addition to dimensional restrictions on the type of vibrators, thin overlays make the use of unusual types of concrete that may require special equipment or procedures for proper consolidation economically feasible.

Felt (*74*) in 1956 reported extensive studies of bonded concrete overlays, describing a number of projects throughout the country. Some of these projects and other bonded-overlay projects were later reviewed by Gillette (*75*). Details concerning the concrete used in these overlays are not given; however, either surface or internal vibration was used. In 1965 Gillette characterized the performance as entirely satisfactory.

The majority of pavement overlays are of sufficient thickness that they are readily placed with conventional slip-form equipment. In these cases no special consideration is needed for consolidation beyond that applicable to new full-depth construction. As the overlay thickness decreases, however, the use of internal vibration becomes more of a problem because the vibrators must operate submerged in concrete with sufficient surcharge to promote consolidation and to reduce damage to the vibrators from overheating. Surface vibration of overlays becomes more practical as the thickness decreases. Because the surface on which the overlay is placed usually provides a comparatively rigid base against which to compact, the effects from surface vibration are improved as noted earlier.

In recent years there has developed a renewed interest in thin overlays either for rehabilitation or as a part of original construction. Iowa used concrete with a quite low slump [¾ ± ¼ in. (19 ± 6 mm)] to overlay deteriorated decks (*76*). The specifications for the vibrating screed required:

> at least one oscillating screed . . . designed to consolidate the concrete to 98 percent of the unit weight determined in accordance with ASTM C 138 by vibration. A sufficient number of identical vibrators shall be effectively installed such that at least one vibrator is provided for each 5 feet of screed length. The bottom edge of this screed shall be at least 5 inches wide with a turned-up or rounded leading edge to minimize tearing of the surface of the plastic concrete. Each screed shall have an effective weight of at least seventy-five pounds for each square foot of bottom face area. [Early consolidation is directed by requiring that] the elapsed time between depositing the concrete on the floor and final screeding shall not exceed 10 minutes.

The placing of such stiff concrete in thin layers requires special equipment; this is because light vibrating screeds tend to ride up on the concrete mass. At least two manufacturers have developed equipment specifically for placement of these overlays. One example is shown in Figure 32.

Portland cement mortars and concretes modified by a latex admixture have been widely used as overlays for bridge decks. The nominal thickness of these overlays varies from about ¾ in. to 2 in. (19 to 50 mm). The overlays are usually placed at a relatively high slump and surface vibration is adequate. Industry literature (*77*) recommends (a) a self-propelled finishing machine with one or more rollers, augers, and vibrating pans with a frequency of 1,500 to 2,500 vpm or (b) a vibrating screed designed to modify composition by vibration with a variable frequency between 3,000 and 11,000 vpm. Equipment such as that shown in Figures 7 and 32 has been successfully used. When the slump is high, care must be taken to avoid excessive vibration that encourages segregation. Development of equipment such as that shown in Figure 32 permits these materials to be placed at lower slumps.

Fiber-reinforced concrete has been used experimentally to overlay both bridge decks and pavements. The inclusion of these needlelike fibers increases the difficulties of compaction. The additional energy necessary to compact the fiber-reinforced concrete depends strongly on the characteristics and properties of the fibers and aggregates. The diameter, length, and volume of the fiber incorporated into the mixture are important; there is a critical fiber content beyond which compactibility is drastically reduced (*78*).

The method of compaction of fiber-reinforced concrete is important because improper vibration can cause rotation and alignment of the fibers. External vibration is usually preferable for stiff mixtures, but on thin overlays surface vibration is the only type of external vibration that is practical, and this probably should be minimized because it results in alignment of fibers. Prolonged vibration encourages bleeding but this does not seem to be harmful. Prolonged vibration should be avoided, however, because it would be expected to cause both alignment and some migration of the fibers because of the differences in buoyancy between the fibers and the matrix.

An extensive experimental paving project in Iowa compared overlays that were fiber-reinforced with those that were unreinforced, mesh-reinforced, and continuously reinforced, in both 2 and 3 in. (50 and 75 mm) thicknesses (*79*). A variety of variables were included and reported by Knutson (*79*), including the fact that, for the fiber-reinforced concrete, pan vibration was used the first day of construction but was later changed to spud vibration. In the 2-in.-thick sections small fiber balls caused many problems by catching and dragging in front of the screed.

In Virginia, 2-in. (50-mm), fiber-reinforced-concrete overlays were placed on two bridge decks as a part of an evaluation of two-course deck construction and several overlay materials. The fiber-reinforced concrete was consolidated by equipment such as that shown in Figure 7. Void measurements made on cores taken from the fiber-reinforced concrete and from a low water-cement-ratio concrete used on other spans showed that the volumes of voids greater than 1 mm (0.04 in.) were the same for both materials (*68*).

Although not strictly a method for consolidation, vacuum dewatering does result in densification of concrete slabs and has been used experimentally for both pavements and bridges, although its major use is for floors and precast elements. With this process, which was patented in 1936 by Billner, a vacuum is applied to the surface of a slab causing free water to be extracted, thus densifying and

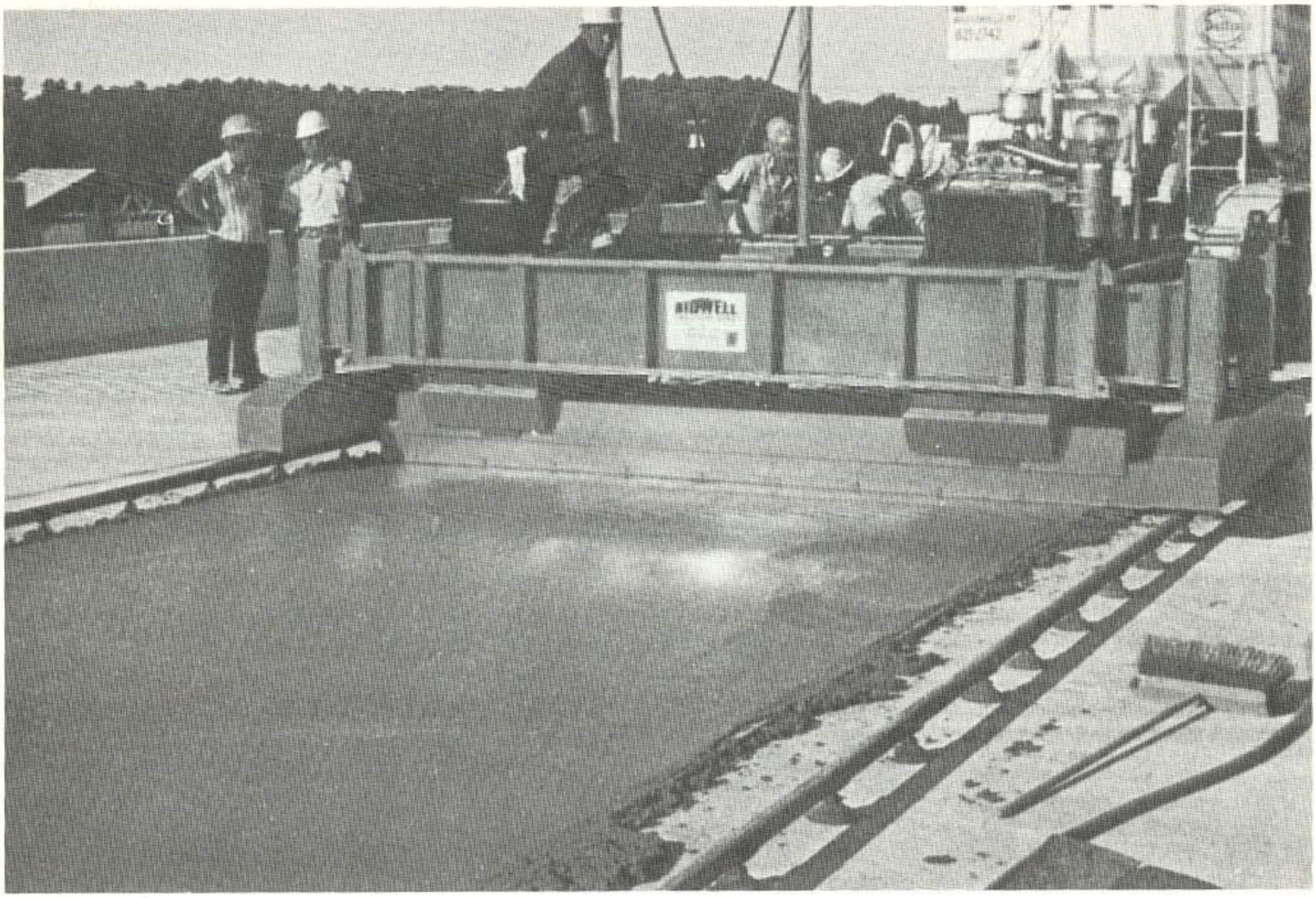


Figure 32. Vibrating screed for placement of thin overlays of stiff concrete.

consolidating the solids. In a summary of the method, Cron (*3*) lists demonstration projects that were constructed soon after the issuance of the patent. These projects include a 60-ft (18-m) lane of the Queensboro Bridge in New York placed in 1936, bonded overlays of pavements in New York and Rhode Island also placed in 1936, and a 2-in. (50-mm) unreinforced overlay placed on 3,500 ft (1 000 m) of US 322 in Grampian, Pennsylvania, in 1938. An additional bridge was treated in New Jersey in 1953. The method was also used by the Bureau of Reclamation on a spillway apron of Shasta Dam. Since these early trials, the process has not been used on pavements or bridges; recently, however, interest has been revived as reflected in reports of experimental placements such as that near Naperville, Illinois, in 1975 (*80*).

Among the benefits ascribed to the process are increased strength, resistance to abrasion, freeze-thaw resistance, and decreased permeability and shrinkage. The process is valuable for concreting under adverse weather conditions, including rain and cold weather. For applications such as pavements and bridge decks, the major disadvantage would be the difficulty of imparting the proper profile and texture in the freshly placed concrete; this is because after treatment the surface is too hard for manual finishing. The process offers promise provided appropriate equipment can be developed.

CHAPTER SIX

CONCLUSIONS AND RESEARCH RECOMMENDATIONS

CONCLUSIONS

Despite the difficulties of confirming under field conditions the specific effects of individual variables associated with consolidation by vibration, the combined results from a variety of field experience, research, and theoretical considerations lead to the following conclusions:

1. Consolidation by vibration improves all of the important properties of concrete in pavement, bridge deck, and overlay slabs. Although useful levels of performance can be achieved with minimal vibration in mixtures of wet consistency, the use of proper vibration techniques can significantly improve the strength, durability, and volume stability by permitting placement of mixtures having substantially lower water-cement ratios than can be placed with less efficient methods of consolidation.

2. The degree of consolidation achieved by vibration is a function not only of the vibrator characteristics but also of the consistency and workability of the concrete mixture being consolidated. The characteristics of the mixture are very important in determining its response to consolidation by vibration. Concrete in the stiff-plastic range [slump approximately 1 to 2 in. (25 to 50 mm)] responds best to vibration of the type used in pavement construction. Concrete with very dry consistency requires substantially more vibration; concretes of wetter consistency [slumps approximately 3 to 4 in. (75 to 100 mm)] require little vibration but are more susceptible to segregation and stratification.

3. Although vibration frequency, eccentric size, and length of time of insertion influence consolidation, there appears to be a fairly large range of values beyond which each of these can vary without substantially affecting the degree of consolidation achieved. Nevertheless, a resonant phenomenon appears to exist, suggesting that there is an optimum frequency range outside of which consolidation is less effective. This frequency appears to be approximately 10,000 to 11,000 vpm, depending on the particular mixture. Likewise, larger vibrator eccentrics [as large as approximately 1⅞ in. (45 mm)] have generally been found to be more effective than smaller sizes. Vibrators with larger eccentrics generally require more maintenance than those operating with smaller eccentrics.

4. Where it can be used, internal vibration appears to be the most effective means of concrete consolidation. Surface vibrators, although used extensively in paving prior to the widespread acceptance of slip-form paving, have reduced effectiveness for slabs greater than 8 to 10 in. (200 to 250 mm) thick and consequently their use is declining; some research has indicated that they require closer control of the mixture to prevent segregation and yet obtain proper consolidation adjacent to reinforcement. Surface vibrators improve the finishability of the surface and are useful for thin overlays and unreinforced slabs less than 8 or 9 in. (200 or 225 mm) thick when placed on relatively rigid bases. Tribe vibrators have never been particularly popular; however, there is increasing interest in operating internal vibrators with the long axis perpendicular to the direction of travel, thus providing a consolidation effort similar to that expected from a tube vibrator. The benefits of this arrangement have not been documented in the literature.

5. Although internal vibration appears to be the most effective method for achieving consolidation in normal highway paving, it requires close monitoring to assure that all vibrators are operating properly at all times and that an adequate head of concrete is maintained above the vibrators.

6. The need for a minimum head or surcharge of concrete over internal vibrators has been discussed in the literature, but little has been done to determine what this minimum should be. Until more definitive information becomes available, the 4- to 6-in. (100- to 150-mm) surcharge recommended by the American Concrete Institute (ACI) may be adopted as a minimum specification requirement. ACI also states that the head or surcharge can be too great, thus restricting the removal of entrapped air.

7. A review of current practices reveals little agreement among specifying agencies as to minimum specification requirements. For paving concrete, vibrator frequency is the most commonly specified characteristic, with minimum values of 7,000 vpm for internal (spud) vibrators, 5,000 vpm for tube vibrators, and 3,500 vpm for surface vibrators being most common. These values are included in the AASHTO Guide Specifications (*81*). As compared with the recommendations of the ACI, the values are slightly low. Idaho 5,000 Idaho? Idaho ✓

8. Vibrator characteristics are even less well defined in specifications for bridge deck construction; minimum frequencies in general are significantly lower than those recommended by ACI. The specifications appear to reflect values that represented the best available equipment when adopted but which have not been changed as available equipment has been upgraded.

9. Although most specifications contain requirements that reflect considerable fear of overvibration, most authorities acknowledge that problems from undervibration are both more common and more serious than those from overvibration and generally agree that overvibration of a properly proportioned mixture is very unlikely. Often when problems associated with overvibration occur, the reaction is to reduce the amount of vibration when the proper course would be to adjust the mixture.

10. Primary examples of poor performance from undervibration are cracking and other forms of distress in areas adjacent to construction joints in continuously reinforced pavements. Because of their location and extra reinforce-

ment, these areas require additional consolidation with immersion vibrators.

11. Although some field trials have been inconclusive, those that have developed significant relationships found that proper consolidation can be achieved with a maximum spacing of 24 in. (600 mm) for internal vibrators for paver speeds up to about 15 to 16 fpm (4.6 to 4.9 m/min) for concretes with slumps of 1 to 2 in. (25 to 50 mm). This finding is consistent with the recommendations by ACI and with geometric considerations. When the paver speed approaches 20 fpm (6 m/min) or when the slump is less than 1 in., a closer spacing is needed.

12. Prolonged vibration results in a significant volumetric loss of air as measured on either the freshly mixed or hardened concrete. This loss is of the entrapped and larger entrained voids. Several studies have shown that the loss of entrained air through vibration is not necessarily detrimental to subsequent durability because the spacing factor, which is considered to be the most important parameter of entrainment, is not significantly changed.

13. In-place density testing with nuclear methods has been used experimentally with encouraging results. Rapid estimates of in-place density would provide input for statistically oriented controls and for remedial vibration under special circumstances.

14. Most currently used laboratory methods for evaluating concrete mixtures use low-energy consolidation methods (i.e., rodding). As a result, the response to consolidation by vibration is not adequately evaluated; because of these methods, sand and water contents are greater than necessary for best response to vibration. To correct this, laboratory methods using consolidation efforts consistent with those to be used in the field should be adopted. The Vebe test, which is widely used in Europe but rarely performed in the U.S., appears to be particularly suited to measuring the response of low-slump concrete [less than 2 in. (50 mm)] to vibration.

15. A simple apparatus for rapid checking of vibrator characteristics when immersed in concrete would be desirable. These characteristics can be readily measured in air with available instruments. Such checks currently are infrequently made.

16. Most of the previous conclusions are drawn from experience with pavements and are applicable to bridge decks and overlays. Overlay technology is rapidly evolving and definitive conclusions at this time are not possible.

RESEARCH RECOMMENDATIONS

Present and past research has been extensively described in this report. There is currently no nationwide research effort on consolidation; however, several agencies continue to pursue local evaluations. The Federal Highway Administration has awarded a research contract for development of a rapid method for in-place measurement of consolidation, which is recognized to be a primary need (*62*).

Among other areas that would benefit from additional studies are:

Materials Studies

1. Laboratory and field procedures for evaluating the response of mixtures to vibration (particularly a review of the Vebe method).
2. Development of admixtures that overcome the tendency for segregation and that provide an improved response to vibration.

Equipment Studies

1. Vibrators that can be rapidly and easily adjusted or that are self-adjusting to accommodate short-term variations in consistency.
2. Evaluation of the effects of orientation of immersion vibrators (i.e., perpendicular versus parallel to direction of travel).
3. Equipment to permit a continuous monitoring of internal vibrators on pavers.

Construction Practices

1. Continued studies to determine cause-effect relationships between practices and performance. It is unlikely that much generalized information can be gained from additional isolated studies such as those in NEEP Project 8 because of the many variables involved and the inability to deal with limiting values (very high or very low) on actual construction. Local studies in which an agency would be willing to make a commitment to a series of studies, each of which would include a very few variables, would be of value. These should involve long sections with few enough variables and sufficient replications to reduce climatic or other isolated influences. The information developed to date by NEEP Project 8 provides a sufficient base of information to establish the variables worthy of study. Many of the variables are much more amenable to laboratory or simulated construction conditions than to field evaluation on actual construction. More use should be made of petrographic examination of hardened concrete in these studies.
2. Studies of poor performance should be documented and reported.

Specifications and Education

1. As given in Table 5, there is a wide variation in current consolidation practices. Agencies should review specifications to insure that requirements are current and reflect practices contained in ACI's "Recommended Practice for Consolidation of Concrete" (*1*). Local information should be developed to establish the necessary levels of in-place density as compared with laboratory values and the distinction between vibrated and hand-rodded methods should be clarified.
2. An effort should be made to impress upon project personnel the benefits to be derived from proper consolidation and the positive returns to be gained from efforts to correct any problems that occur by means other than reducing or eliminating vibration.

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APPENDIX

CONSOLIDATION QUESTIONNAIRE

SPECIFYING AGENCY

Considerable emphasis is being placed on vibration and its effects on concrete pavements by many specifying agencies and research and industry organizations. Also certain problems in completed pavements have been blamed on improper vibration. In order to review these problems and to assemble data on current practices and other information necessary to develope recommendations on proper consolidation of concrete pavements, the Highway Research Board Committees A2F01 on Rigid Pavement Construction and A2F06, Highway Equipment, request that you complete the following questionnaire.

1. What types of vibration do you use:

	Require	Allow
a. Surface pan?	3	25
b. Spud?	9	23
c. Tube?	2	23
d. All?		11
e. Other? ____________		

Additional Comments:
- a. Surface pan
  - 1 Required for CRCP only.
  - 1 Requires internal vibrator at edges plus pan or full width internal vibration.

Other:
- 1 Allows tube on 2 course construction along with spud vibrators.
- 1 Vibrating mesh depressor or screeds.
- 1 Spud used as only vibration at longitudinal and transverse joints.

2. What do your specifications require for internal vibration in relation to:

a. Spacing

Not specified	26 states
18"	3
24"	7
30"	5
As recommended by manufacturer	1

b. Frequency

Not specified		2		
3500 + VPM		2	Surface	Hand operated 3
3600 + VPM		1		
4000 + VPM		2	Pan	
4500 + VPM		1		
5000 + VPM		5		
5000 + VPM	-Tubes	9		
5300 + VPM		1		

6000 + VPM	1	
7000 + VPM	15	Spud Vibrators
7500 + VPM	1	
8000 + VPM	1	Spud
10800 + VPM	1	
5000 - 10,000 + VPM	1	Spud
3500 - 7000 + VPM	1	

c. Amplitude:
   Not specified -32
   Sufficient to be preceptable a surface- 5
   As recommended by manufacturers- 1

d. Horizontal position:
   1. 7" pavement ________ inches? Not specified 39
   2. 8" pavement ________ inches? Not specified 39
   3. 9" pavement ________ inches? Not specified 39
   4. 10" pavement ________ inches? Not specified 39

   1 Depth of reinforcement determines vibrator placement.
   1 Placed to clear reinforcement.
   1 At midpoint of slab.

e. Angular position in longitudinal plane? Not specified 37
   2 As recommended by manufacturer.
   1 10° +

f. Is size specified? No. 40

g. Forward travel speed of equipment _______ feet per minute.
   Not specified 32
   1 At least 2 feet per minute.
   1 6 feet per minute maximum.
   2 Speed geared to concrete production for continous forward movement.
   1 Vibrating equipment matched to speed.
   1 Vibrator stopped when spreader is stopped.
   1 Vibrators stopped if stop exceeds 15 seconds.
   1 Maximum 5 seconds vibration in one place.

3. What specific problems can you relate to vibration? Describe.
   a. Surface____

   7 Excessive vibration brings excess mortar to surface which wears away.
   12 Causes excess mortar on surface.
   1 Excess vibration brings shale and coal to surface causing popouts.
   1 Excess vibration causes segregation and problems with edges with slipform paving.

b. Segregation ______

8 Excess vibration causes settlement or segregation of coarse aggregate.
1 Excess vibration causes water to accumulate along steel mesh.
1 Segregation only occurs with slipform pavers with stiff mixes and rapid travel. (This may be lack of consolidation of stiff mix.)
1 Segregation no problem even with heavy vibration.

c. Reinforcing joints ______

8 Inadequate consolidation at construction joints causes problems in CRCP.
1 Hand vibration required 5 feet on each side of construction joint in CRCP.
1 Lack of adequate consolidation causes concrete to slump between steel.
2 Vibration causes dips in surface at doweled joints and mesh laps.
2 Lack of consolidation sometimes present at keyed longitudinal construction joint.
1 Concrete hangs up on re-steel if not properly consolidated.
2 Concrete not consolidated at steel and mesh laps.
3 Displace reinforcement or dowels.

d. Entrained air content ______

1 Minor loss with vibration.
1 1 to 1 1/2 % loss.
1 No loss even with heavy vibration.
1 No difference with vibration.
1 Up to 1 1/2% loss from finishing equipment and vibration.
1 Reduced with excess vibration.
1 Pan type causes loss of air at surface.
1 Inconclusive results.

e. Other:

1 Isolated areas of CRCP failure appear to be due to lack of vibration.
1 Edge slump and roughness may be effected by vibration.
1 Causes displaced steel.
2 Lack of consolidation results in honeycomb at keyed longitudinal joints and transverse joints.

f. Please identify those related to internal vibration.

- 1 Internal vibration improves lower layers more than surface.
- 1 Accumulation of water along mesh.

4. What frequency and amplitude is required for:
   a. Surface pan vibration?
      - 22 3500 VPM
      - 3 3600 VPM
      - 1 4000 VPM
      - 1 Manufacturers recommendations.
      - 5 Pan not specified.
      - 2 Pan not permitted.
      - 1 Frequency necessary to consolidate the concrete.
   b. Tube vibration?
      - 21 5000 VPM
      - 3 3500 VPM
      - 1 7000 VPM
      - 1 3600 VPM
      - 1 4000 VPM
      - 1 4500 VPM
      - 6 Not specified
      - 1 Tube not effective.
   c. Are there any limits placed on the use of either type?
      - 14 No limits placed.
      - 3 Automatic shut off of vibrators when equipment stopped.
      - 1 Surface pan not allowed on lower course of 2 course pavement.
      - 1 Slipform requires speed vibrators.
      - 1 10,000 VPM maximum for either type.
      - 1 Use of pan optional with engineer.
      - 1 Tube not allowed.
      - 1 Pan on top course only and not over transverse joints.
      - 1 Surface pan not permitted.
      - 1 Must produce 98% of rodded density.
      - 2 Positioned to miss steel in pavement.
      - 1 Surface pan for 2 lift construction and internal for full depth. Both types may be used concurrently at the engineers discretion.
      - 1 All types but multiple spud must be approved by engineer.
      - 1 Tube not in contact with concrete long enough and has frequent breakdown.
      - 1 Pan permitted on slipform if part of machine.
      - 1 Surface pan not allowed on slipform.

5. Do you require the use of or use a tachometer or other testing devices to check VPM's for vibrators?

21 Yes
21 No
1 Rarely
1 Contemplate use

6. Do you check the adequacy of vibration when work begins or any other time? ____________

9 Yes 8 No
22 Check by visual observation and cover.
1 By 1000 feet test section
1 VPM of vibrators checked.

7. What type of testing equipment is needed? ____________

6 Test device to check density of plastic concrete.
7 Tachometer.
1 Vibrator meter or indicating device.
5 Core drill.
1 Non destructive means of determining proper consolidation.
1 Tachometer, amplitude indicator, and fluid pressure indicator.

8. Has your agency conducted field or laboratory research on vibration?
14 Yes 28 No

If a study was conducted, what were the significant findings? If a report is available please submit a copy.

1 9000 VPM + and 1 7/8 " diameter @ 24" spacing will provide adequate consolidation.
2 Study now in progress.
1 Useful air hard to remove - good bubble count and spacing even after gross overvibration even though total air down to 1%.
1 Vibration study found that concrete with slump of over 1" had higher density than minus 1" slump concrete.
2 No segregation of coarse aggregate caused by vibration.
1 Mesh position not varied by vibration.
1 Study indicates that uniform concrete could be obtained within the following limits:
1.) 8-12 FPM paving speed.
2.) Vibrating frequency of 7000 - 9000 VPM.
3.) 8 to 12 vibrators per 24 foot pavement width.

9. **Comments** ______

1 Vibration no problem if conducted properly.
1 Spud vibrators give best results when properly used.
1 Need to develope proper VPM/Amplitude criteria to produce consistent quality pcc pavements.
1 Tube vibrators not predently used in state.
1 Compaction increases with higher frequency
2 Need nuclear densometer to measure consolidation.
1 Should specify foot - lbs. of energy per unit volume of concrete.
1 We write specification as end result.
1 Contemplate use of 97% of rodded density as specification requirement. This was developed from field research using nuclear gauge.
1 Vibrator manufacurers should adopt a standard rating system taking into account the weight and swing of the eccentric and velocity and weight of the vibrating body
1 Would like correlation between amplitude and frequency and need criteria for maximum and minimum time of vibration at specified frequency and amplitude.
1 Have noticed on some pavements that when re-steel pavement is being placed by slipform paver that excessive vibration near the transverse wires induces collection and flow of free water to outside edge of pavement causing edge slump.

CONTRACTORS

1. Do you change vibrators from project to project? 13 Yes / 32 No

   a. If yes, why do you change?

   Because of:
   1. change in mix design
   2. state specifications or project engineer's preference
   3. change for different pavements - CRCP, RC, or plain
   4. change in thickness of pavement
   5. high production needs additional vibration

2. Do you normally adjust vibration after beginning paving operations? 23 Yes / 22 No

   a. Horizontal position 25 Yes / 8 No

   b. Explain

   Because of:
   1. increase vibration for low slump - decrease for high slump
   2. use constant frequency and adjust vibrator elevation for best surface behind extrusion plate
   3. adjust for edge slump
   4. adjust to miss steel
   5. adjust to desires of engineer
   6. adjust for pavement thickness
   7. mesh has tendency to drop below desired elevation with some mixes, so adjust vibration

3. Do you change frequency, spacing, and/or horizontal position if you change the forward speed of the equipment? 5 Yes / 38 No

   a. If increased speed, how changed?
   1. speed up generator
   2. increase number of vibrators
   3. vary speed of tamping bar with forward speed
   4. vibrators set for speed of paver

   b. If decreased forward speed, how changed?
   1. lower generator speed
   2. increase vibrator spacing to maximum allowed
   3. attempt to run at uniform speed

4. **Do you feel variations in paver speed (say between 5 and 20 feet per minute) have a significant effect on consolidation with no vibrator adjustment?**

10	Yes
22	No

1. not as long as slump is between 1 1/2 and 3 inches
2. only at speeds below 5 feet per minute
3. occassionally if vibrator specing or frequency is borderline for mix used
4. proper horizontal spacing will provide proper vibration
5. will depend upon the concrete mix
6. no significant effect in 5 to 15 feet per minute speed range
7. frequency should be matched to speed above 5 to 6 feet per minute
8. too much vibration could cause segregation
9. no change for 8 to 12 feet per minute but need change for range shown
10. attempt to maintain uniform speed
11. speed controlled by depth of pavement (i.e. 6" or 15")
12. not qualified to answer

5. **What specific problems have you had that you feel are attributed to vibration?**

21	None

1. drifting of concrete on superelevated curves
2. slurry produced in area of vibrator rack
3. lack of vibration at headers
4. light weight particles rise to surface and are deposited in depression causing isolated areas of popouts
5. insufficient vibration causes honeycomb or open surface
6. surface irregularities caused by vibrators contacting reinforcing steel or dowel baskets
7. cause movement of steel
8. vibration causes higher concrete overrun
9. have had slight depressions in vibrator track
10. additional vibrators needed in pavements over 15"
11. vibrators unable to consolidate concrete under steel in continuously reinforced concrete pavements when slump is less than 3/4"
12. on form paving, the speed of spreader is more critical than on slipform paving since the concrete is vibrated after it is spread
13. certain limestone mixes have frothing action leaving scum on surface
14. must be careful of slurry in the vicinity of vibrators

6. In slipform paving, what distance from the edge is the vibrator placed?

2 to 4 inches	1	10 to 12 inches	11
4 to 6 inches	6	14 inches	1
6 to 8 inches	5	15 inches	2
8 to 10 inches	5		

1. Varies with slab depth
2. put extra vibrators as close to edge as possible (2 inches) to get uniform flow of grout to edge

a. Should this vibrator be the same frequency and amplitude as the others? 32 Yes; 1 No

1. frequency and amplitude should be less (one reply)

b. If changed, what is your recommendation?

1. visual inspection of edge

7. With which type of vibrators have you had experience? Which do you use and its application?

a. Spud (44)

Experience:
1. use on slipform and form paving
2. especially good in harsh mixes
3. hard to control with over vibration in areas (one reply)

Use:
1. slipform and form paving
2. form spreaders
3. front of twin screed on form paving

b. Surface pan (24)

Experience:
1. with pan type finisher on forms
2. back up system for spuds on slipform
3. on older paving equipment
4. helps in finishing
5. unsatisfactory because of honeycomb under steel
6. use on slipform

Use:
1. use on street paving
2. used on streets, highways, and airport paving
3. suspended behind spreader and recommended for pavements up to 16 inches thick

c. Tube (9)

Experience:
1. used on slipform paver
2. in front of main pan on slipform
3. tends to overload finishing machine

4. used on variable width pavements
5. had limited but unsatisfactory experience

Use:
1. used on older equipment
2. good on slipform

d. Other (4)
Experience:
1. vibrating screed boards on finishing machine

Use:
1. city streets
2. on metering screed

8. For the vibrator types for which you have had sufficient experience to evaluate, do you feel present vibration is:

	Excellent	Good	Adequate	Poor
Spud	19	15	8	1
Surface Pan	4	9	9	5
Tube	2	3	1	3
Other		3		

9. For any listed as adequate or poor, do you have any recommendations such as changing spacing, frequency, amplitude, etc., that would improve results?

1. automatic controls for spud vibrators to vary vibration with slump and speed
2. spuds work better when synchronized with speed and automatic shutoff when paver stopped
3. recommend discontinue surface pan or tube
4. spacing should be dependent upon type of material and slump
5. vary frequency and amplitude to match slump and mix being used
6. increase amplitude

10. Is your paver equipped with a tachometer or other instrument to monitor frequency of vibration?

9	Yes
26	No

1. use meter to show frequency
2. use voltage meter on generator
3. use tachometer
4. monitor voltage and frequency from respective meters to assure vibrators performing

11. If No. 10 is yes, do you have any information (or opinion) in regard to uniformity of frequency?

1. use tachometer to maintain RPM
2. run at 180 cycles and frequency is uniform
3. frequency meter corresponds closely to tachometer
4. voltage regulated by electrical system for uniform vibration
5. uniform as long as generator is at proper RPM
6. once set, frequency does not vary much
7. frequency depends upon generator frequency, size of vibrator, and slump

12. If No. 10 is no, do you use a tachometer on the job for checking vibration?

	17	Yes
	17	No

a. How often is it used?

several times daily	2
daily	4
weekly	2
monthly	1
start of job	3
start of job, and 2 or 3 times daily	3
as conditions warrant	2
seldom	1
not at all	1

b. In the air?

12	Yes
4	No

c. In the concrete?

8	Yes
5	No

MANUFACTURERS

1. What types of vibrators are satisfactory for a pcc pavement consolidation, and what types are not?

	Preferred		Acceptable	Not Acceptable
Surface Pan			2	1
Spud	3			
Tube			2	
Other	1 tamper			
Combination	2	of	spud & tamper, spud & pan	

2. With respect to the preferred or acceptable types in No. 1, what limits or modifications, if any, would be appropriate in connection with the following:

Thick pavement:
1. additional spud units needed
2. use internal spud
3. embedded items must be considered

Thin pavement:
1. no limitations (2)
2. use internal spud with light eccentrics

Little or no reinforcement:
1. no limitations
2. use internal spud

Heavy reinforcement:
1. use internal spud with heavy eccentrics
2. vibrators run too close to surface
3. location of steel must be considered

Concrete placed in two lifts:
1. no limitations
2. use vibration on first lift
3. use spud vibrator on first lift and spud plus pan on second

Concrete placed through reinforcement:
1. no limitations
2. location of steel

Steel placed through concrete:
1. no limitations (2)

Fixed of slipforms:	1. use spud vibrators 2. no limitations (1) 3. slipform paver requires dryer mix and hard to place through reinforcement
Large size aggregate:	1. use spud vibrators with eccentrics to match aggregates and slump 2. diameter of vibrator should equal largest aggregate size 3. tamper should be required in addition to spuds
Sandy mixes:	1. no limitations 2. more edge vibrators away from edge 3. use internal spud with light eccentrics
Spacing of internal vibrators:	1. depends on slab depth, slump, aggregate size, and size of eccentrics 2. depends on mix design 3. depends on embedded items
Consistency of concrete:	1. very important - use whatever slump necessary to do best job 2. match eccentric to slump, aggregate size, and slab depth
Travel speed:	1. match number of vibrators, eccentric size, and frequency of vibrator (vpm) to speed 2. 23 feet per minute appears to be the limit for spud vibrators at 20-inch spacing 3. no relationship

3. Would you recommend on-the-job checks for adequacy of vibration? 3 **Yes** ___ **No**

If yes, on what basis?

visual	1	visual uniformity	1
tests for uniformity	2	surface appearance	2
tests for frequency	3	other core drill	

4. Would you recommend devices for operator-monitoring of vibration? What type?

a. frequency meter on generator output

b. tachometer:
1. not recommended (1)
2. use phototach or vibratac at the vibrator

c. finger probes which, by means of an oscilloscope, would show the energy or frequency of vibration:
1. not recommended (1)
2. use transducer device (not yet ready)

d. other (explain):
1. the 180 cycle spud vibrators are frequency sensitive; therefore, if you have monitor on frequency, you will monitor the vibration, whether or not the vibrator is operating
2. use nuclear device to check density

5. What adjustments of vibrators, if any, are recommended at the job site; and what job-factor variables would warrant these adjustments?

Spacing of internal vibrators:
1. need full consolidation across slab
2. depends on slab depth and speed of paver

Frequency:
1. use 9000 vpm plus
2. usually at 9600 vpm - some states limit to 6000 vpm

Amplitude:
1. maintain high frequency and adjust amplitude with various available eccentrics
2. reduce for wet or sandy mixes
3. change as mix design requires

Travel speed:
1. must consider all of the above statements
2. current information indicates this is not a problem
3. add vibrators for increased speed

Other:
1. use individual vibrator circuit breaker switch (combination) which would permit shutting off some vibration if mix design changed or delivery of concrete slowed down
2. reducing generator RPM not recommended

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