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Efficiency of Vibrators in Consolidating Paving Concrete

Final Report

F. E. LEGG, JR.

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Michigan Department of State Highways and Transportation
State Highways Building
Contract No. 73-0764
Lansing, Michigan

THE UNIVERSITY OF MICHIGAN 1817

Department of Civil Engineering

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COLLEGE OF ENGINEERING
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1. INTRODUCTION

Fresh air-entrained concrete consists of a mixture of mineral aggregates in a suspension of water, finely ground portland cement, and well dispersed microscopic air bubbles. Occasionally, there are gross air voids. If there is a high concentration of water in the mixture so as to promote settlement of the mineral aggregates in the cement-water-bubble paste, the concrete will be characterized as having a high slump, often accompanied by segregation and a weakened final structure due to excessive dilution of the cement paste constituent.

Well proportioned paving concrete will have a carefully controlled balance of ingredients so as to contain just sufficient water to lubricate the mass to allow proper consolidation. The inverse relationship between concrete strength and water-cement ratio provides incentive to seek higher strengths by diminishing the water content. If water reduction is carried too far, however, lack of fluidity of the paste constituent will inhibit mobility of the entire mixture and prevent thorough compaction. This conflict of factors is central to concrete technology; i.e., personnel responsible for placement of the concrete in the structure desire a more fluid mixture of higher water content for easy compaction while those aware of the accompanying loss of durability, lack of strength, and proneness to segregation due to excessive fluidity favor the stiffer mixes of lower water content.

As far back as 1910 (1), it was known that some reconciliation of these two conflicting tendencies could be made by imparting vibration to the fresh concrete or by jigging it. Such vibration allows mixes, despite being stiff and perhaps of low water-cement ratio, to be readily consolidated even into intricately shaped forms or where there is congested reinforcement. This development has been exploited during the past 60-odd years but to a great extent on an empirical basis. The major effort has been for vibrator manufacturers to develop more powerful and reliable equipment to meet industry demands, particularly for precast products such as masonry units or for prefabricated wall panels. Vibrators suitable for permanent attachment to re-usable forms have been particularly well developed.

The present study is concerned with consolidation of paving concrete, and the following sections emphasize compaction of flat slabs on a subgrade.

Two items of national scope make it timely that work now be undertaken regarding consolidation of paving concrete:

1. The National Experimental and Evaluation Program ("NEEP") in the FHWA Informational Memorandum CMPA-20-70 dated July 15, 1970 proposed that, "Proper Vibration of PCC Pavements" be studied. The introductory paragraph of this announcement is quoted in full,

> "Although numerous studies have been made on vibration of concrete, little information is available concerning the effects of vibration on concrete pavements. Throughout the country, engineers have expressed concern either that pavements may not be receiving optimum consolidation or that the mix ingredients may be segregating. These questions have been brought to the attention of various organizations. As a result, the performance of vibratory equipment in PCC pavements has been identified as a top priority research item by a number of organizations, including the Portland Cement Association, the American Concrete Paving Association, the Highway Research Board, and a Subcommittee of the AASHO-ARBA Joint Cooperative Committee."

The highway departments of nine states have, so far, cooperated in this program: Alabama, Colorado, Illinois, Indiana, Kentucky, Mississippi, New York, Texas, and Utah. Results of some of the work of these agencies are now available and will be summarized later.

2. The American Concrete Institute in the ACI Journal of July, 1971 appealed for research effort on concrete consolidation as follows:

> "American Concrete Institute Committee 114 on Research and Development has compiled a list of the research subjects of most critical importance to the continued advancement of concrete technology. High on the list is 'consolidation of fresh concrete.'
>
> "The properties of hardened concrete and its performance in a structure are critically affected by the methods of consolidation used during placement. Elimination of internal and surface voids, achievement of complete bond with reinforcing steel and previously placed concrete, and optimum strength and impermeability, are primary objectives. At the same time, compactive effort must not be uneconomically excessive or improper for the particular placement conditions lest harmful bleeding and segregation occur. The ideal economical solution would be to apply exactly the correct amount of the right kind of compaction, but no more, to assure maximum enhancement of the benefits.
>
> "ACI Committee 309, Consolidation of Concrete, has called attention to the lack of quantitative information to permit reliable decisions as to methods and amount of compaction needed for a particular structural element. Among the factors needing detailed study are: methods of measuring degree of consolidation and determining the volume of concrete affected by vibration in any given procedure; amount of energy required for vibration to fluidize the concrete mass; factors affecting the transmission of vibratory energy through fresh concrete, and its rate of attenuation; the resonant frequency of the vibrating system and the variables which affect it; influence of such characteristics as aggregate size, mixture proportions, and consistency of the concrete on the response to vibration; and the relative efficiency and economy of various vibration methods.
>
> "Prospective sponsors of such research, organizations or groups wishing to undertake such research and competant to do so, and those interested in cooperative or coordinated research and development on this subject are invited to contact Committee 114. The Committee will then attempt to establish contact between interested sponsors and qualified researchers for negotiation of a specific program and financial arrangements. Sponsors and researchers will be encouraged to call on ACI Committees 114 and 309 for consultation in conducting the program. The researcher will also be urged to keep the two ACI Committees informed of progress and to publish results of the research

> in such a manner that they can be made readily available for application by the concrete construction industry."

Reference 19 specifically cites the urgency of needed improvement in consolidation of concrete resulting from Virginia's observations of performance of its continuously reinforced pavements. The failed sections of pavement were paved by slip form paver employing spud vibrators at an unknown spacing and frequency.

2. GENERAL OBSERVATIONS ON CONSOLIDATION OF PAVING CONCRETE

2.1 NEED FOR CONSOLIDATION

Paving concrete is normally deposited on the prepared aggregate base from hauling units or other means of conveying concrete to the site without too much attention to spreading it uniformly. The latter step is accomplished by a spreader most often having an auger (screw conveyor) rotating on a horizontal axis which is transverse to the direction of travel of the paving train. The auger height is set so as to strike off the concrete at about the correct elevation to provide the proper amount of surcharge for subsequent finishing operations.

The passage of the spreader constitutes the first step in "consolidation" of the concrete and all subsequent steps including strike-off, oscillating screeding, internal or surface vibration, or both, aim to provide that the concrete be homogeneous and shaped to conform strictly with line and grade.

It is inevitable that the concrete will contain some entrapped air voids and that passage of the spreader will result in occasionally folding the concrete over to trap additional pockets of air, particularly at the junction of different batches, and likewise intimate contact with the granular base at all points will not have been established. Voids will be particularly prevelant in areas where there is a tendency for segregation of aggregate sizes.

If subsequent operations are unsuccessful in removal of the voids, the concrete will be variously characterized as having "honeycomb," "ratholes," or "bugholes." The latter term seems most often used to describe the blemishes observed on formed vertical surfaces. It is generally conceded that a minor amount of such gross voids will not importantly impair the structural behavior of the concrete; however, a concentration of such voids are undoubtedly detrimental if they actually reduce the cross section of sound concrete. Too, if adjacent to reinforcing bars, they may serve to pocket corrosive chloride solution, etc.

The gross air voids, also designated "entrapped" air, are to be distinguished from the beneficial entrained air which consists of a well dispersed system of microscopic air bubbles, generally less than about 0.01 in. in diameter.

The exact mechanisms involved in "consolidation" of concrete have variously been considered as covering quite a range of events as well as having a very restricted meaning. If the entire range of possible concretes be considered, varying from the harsh, dry mixes used, for example, in building block manufacture all the way to the highly plastic, very fluid mixes, the definitions of compaction by vibration proposed by Kolek (2) are probably most appropriate. He considers compaction as falling into three stages:

> "The first stage, called 'initial settlement,' consists of a general subsidence or packing of the particles similar in principle to the packing of granular materials. Before this stage of the compaction process sets in, the concrete mix can largely be regarded as a mass of separate particles surrounded by mortar and held in this condition by the arching action of the larger particles and prevented from falling to a lower level by static friction and, partly, adhesion. This state of apparent equilibrium is not stable and, as soon as the static conditions change to dynamic through the action of vibration, the system collapses. This stage of change, called the 'initial settlement,' is the first stage in the process of consolidation. At the end of this stage the top level of the concrete has subsided by a considerable amount indicating that the relative distances between the previously separate particles have diminished on the average by the same ratio. The end of this stage is characterized by the closure of the surface, the formation of a continuous matrix of mortar enclosing the coarse aggregate, and the entrapped air bubbles. Whereas before the

> onset of this stage the concrete was a mass of loose particles, at the end of this stage the concrete has all the characteristics of a heavy viscous fluid.
>
> "The second stage, called 'deaeration,' consists of a general redistribution of the coarse aggregate within the continuous matrix of mortar and the expulsion of the entrapped bubbles, which find their way upwards. Whereas in the previous stage the shape of the coarse aggregate particles was of decisive importance, in this stage the mortar or in particular the thixotropic cement paste assumes the major role. Tattersall, working with cement pastes and using a rotation viscometer, found that under shear cement pastes yield and the viscosity breaks down under continuous shearing. It can be assumed that a mortar composed of cement paste and fine aggregate behaves in a similar fashion and that the shearing action caused by the passage of a train of vibration waves will break down the viscosity of the matrix and thus facilitate the redistribution of the coarse aggregate and the escape of the entrapped air bubbles. The second stage in the consolidation process can be regarded as completed when the surface glistens with moisture and is no longer disturbed by any major eruptions of entrapped air.
>
> "The third stage, called 'stabilization,' consists of a general interlocking and, should this phase be unduly prolonged, separation of the constituents of the mix might ensue. At the onset of this stage the process of consolidation may be regarded as finished as its continuation is unlikely to have any advantageous effects on any property of the concrete."

The ACI Recommended Practice for Consolidation of Concrete (ACI 309-72) has adopted a more restricted definition by stating, "Consolidation, also called compaction, is the process of removing entrapped air from fresh concrete in the form" (3). It is to be observed that removal of entrained air is purposely omitted from the statement since such removal would be detrimental.

2.2 BASIC MECHANISM OF CONSOLIDATING CONCRETE BY VIBRATION

The following statements of T. C. Powers (4) provide a useful starting point for discussion of the basics of vibration consolidation of concrete:

> "We visualize freshly mixed cement paste in the quiescent state as a three-dimensional network of particles in water, the particles

> being held together, and apart, by small interparticle forces acting across very small spaces between the points of near contact between particles. In a paste of ordinary composition, these forces are such as to give the paste the properties of a weak solid. The stiffness of the paste will naturally be some function of the total number of points of virtual contact between particles and of the intensity of forces of interaction at those points.
>
> "... the mechanical action of vibration is described; it is considered to be a process of generating compression waves which moves the water molecules much more than it does the solid particles of cement and rock. This amounts to a back-and-forth flow of water between the particles, the relative motion generating hydraulic pressure. The pressure is highest where the restriction to flow is greatest, namely at points of virtual contact between particles. ... any widening of the gaps between particles at points where the particles are closest together, nearly in contact, results in a reduced van der Waals attraction at those points. If the gap width becomes doubled, for example, the attractive force might be decreased to perhaps 1 percent of what it was before. Since the total attractive force in cement paste is not very high, such a reduction could mean that the effects due to interparticle attraction might be practically wiped out by vibration. Experiments show that cement paste and concrete does become converted from a plastic solid to a fluid, and that state persists as long as the vibration continues, but, the fluid state is thixotropic, not Newtonian."

This quotation gives a very acceptable explanation of the "fluidizing" effect of vibration observed by anyone who has worked with concrete wherein internal vibration will be noted to cause the concrete to lose its rigidity and flow readily under the force of gravity. Likewise, a sheen appears on the surface of the concrete adjacent to the vibrator indicating continuity of the liquid phase and its dominance at the very surface of the concrete; gravity is causing settling of the mineral aggregates in the fluidized matrix and upward migration due to bouyancy of the gross air voids is indicated by their frequent bursting from the concrete surface.

The oscillating movement within the concrete is generated by vibrators either of the electromagnetic or of the rotary type. The rotary type imparts oscillations either internally by direct immersion in the concrete or externally through the formwork or on the top surface by vibrating screed or sliding shoe or plate. Power is supplied electrically or pneumatically. So far as known, the electromagnetic type has been used only externally mounted on the forms.

It is customary to treat the movement of vibrators as a case of simple harmonic motion where the analytical treatment of displacement of the device, itself, acceleration, eccentric moment, etc., is reasonably straightforward. Appendix A (3) gives the fundamental relationships.

3. CRITERIA FOR ADEQUACY OF CONCRETE CONSOLIDATION

3.1 GENERAL

Visual observation of voids adjacent to reinforcing bars, honeycomb, etc., upon examination of drilled cores is, of course, the most compelling indication of lack of adequate consolidation. However, such visual observation does not permit measurement of the degree of improper compaction, and numerical methods to do this have been sought, some of which are enumerated below.

3.2 DENSITY MEASUREMENTS OF DRILLED CORES

Many investigators have used unit weight measurements of drilled cores as a means of assessing efficiency of consolidation. For example, Bower and Gerhardt (5), obtained cores both within the pathway of immersed spud vibrators and midway between adjacent vibrators in a full-scale paving operation in Colorado. The density of the cores in the vibrator path tended to be higher, in some cases as much as 6 lb/cu ft indicating greater success in expulsion of air voids in close proximity to the vibrator. The vibrators were ineffective in consolidating the concrete at distances of 25-30 in. from the vibrator path. Weighing the cores in air and when immersed in water provided a precise displacement measurement of concrete density.

In another case, using only surface vibration as a means of consolidation of a very dry concrete, the Road Research Laboratory of Great Britain studied the density of 2-in. thick slices of cores drilled from an 18-in. thick experimental pavement (6). Typical results are shown in Figure 1. It is noted that in this particular case surface vibration was ineffective below about 8-in. from the surface of the slab.

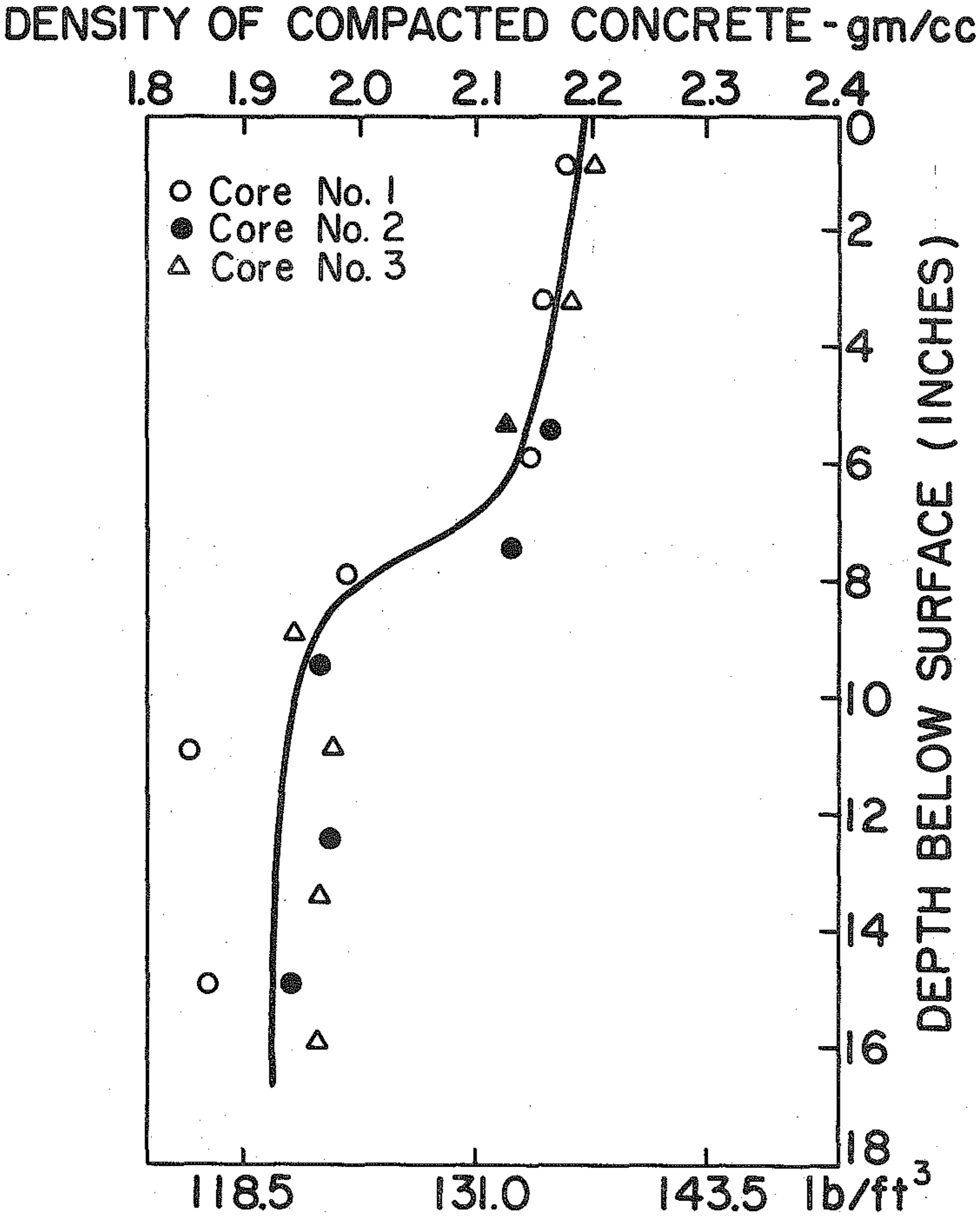


Figure 1. The variation in density of hardened concrete with depth (from Ref. 6).

Other investigators (7) have not been entirely satisfied with the density determinations derived from water displacement measurements since it was obvious that some of the water entered gross voids apparent on the surface of the core upon immersion and thereby yielded a fictitiously small observed volume; as a consequence greater density and an improperly high degree of consolidation would be deduced. By cutting the ends of drilled cores strictly at right angles to the core axis and making very careful measurements of core diameter, the gross volume could be more accurately computed.

3.3 MISCELLANEOUS CRITERIA

Drilling of cores and making subsequent measurements thereon is, of course, tedious and cumbersome and preferable techniques have been sought. Some success has been reported using gamma ray techniques (8), ultrasonic pulse velocity, and Swiss Hammer (9) to assess the concrete strength or density nondestructively.

Strength of the hardened concrete in compression from drilled cores and in flexure from sawed beams, have also been tried by investigators as a measure of compaction. Kolek (8) concluded from his tests that crushing strength "would be a very poor method of determining the efficacy of internal vibrators."

Elastic modulus determinations were made by the Colorado investigators (5) and it was concluded that, "Modulus of elasticity readings determined by sonic and pulse wave velocity tests show that the soundness of the concrete is improved by good vibration."

It should be emphasized that practically all of the techniques mentioned above involve tests of the hardened concrete and are therefore "after the fact" tests; as such, they may be useful for research to discover trends, etc., but are not helpful in control testing where immediate detection of short-comings in compaction is desired. The latter is the major aim of the current investigation.

4. VARIABLES AFFECTING CONCRETE CONSOLIDATION

Many have given attention to the parameters influencing the consolidation of concrete, including those classified as strictly consolidation techniques as well as characteristics of the concrete itself which contribute to its successful consolidation. Forssblad (10) suggests the following parameters as being influential with regard to internal vibrators:

"a. Internal vibrator's construction and vibration details: Probe diameter; probe length; weight and weight distribution; vibration data:

   (1) Frequency

   (2) Amplitude

   (3) Acceleration

   (4) Distribution of vibrations along the probe

b. Internal vibrator's handling and concrete placing technique: Time for immersion, vibrating in immersed position, and withdrawal; immersion depth; inclination of probe; distance between immersion points; lift thickness during filling of the form with concrete.

c. Characteristics of the concrete: Consistency (workability); cement content; aggregate's maximum particle size, gradation, particle shape, specific gravity, etc.; temperature; time lapse between mixing and vibration.

d. Form work and reinforcement: Size of the form; form construction; reinforcement."

Kirkham (6) considered the following variables significant with respect to surface vibrators:

"(1) The frequency of vibration (i.e., rpm, vib/min)

(2) The amplitude of vibration

(3) The direction of vibration

(4) The wave form

(5) The forward speed of travel

(6) The weight of the beam (screed) and its method of support

(7) The shape of the shoe fitted to the underside of the beam."

Sugiuchi (11) provides a very comprehensive study of the research on concrete vibration undertaken prior to 1967 and calls attention to other matters such as attenuation of vibration (decrease in amplitude, pressure, etc.) at increasing distance from the vibrator. He also points out significantly that:

> "The rheological behavior of concrete provides conclusive evidence that some threshold force is required to initiate a breakdown in the structure of freshly mixed concrete. Hence the observation that some minimal acceleration in the concrete or some minimal amplitude of vibration is required for rapid compaction correlates quite well with the concrete's rheological behavior."

Reference 16 provides further insight into rheological behavior by study of cement pastes, and it follows from the data that the chemistry of the cement, temperature, water-cement ratio, and duration of time between mixing and vibration will each have an influence on the effectiveness of vibration. The thixotropic behavior of concrete is well recognized particularly for that containing retarding admixtures wherein plasticity of such concrete often can be restored, even after several hours, by vigorous revibration (25).

Bennett and Gokhale (12) assess work previous to their own as follows:

> "The vibration characteristics which may be considered as of possible importance are the frequency, amplitude, acceleration, maximum velocity, and power required to accelerate a unit mass

> of concrete in any quarter cycle of vibration. Many investigators have considered the acceleration to be the most significant parameter. Davies, Green, and Plowman hold this view which has been endorsed by the report of the Institutions of Civil and Structural Engineers, with 4 g to 7 g recommended as a suitable range of values. Cusens, however, suggests that the importance of acceleration applies mainly to clamped moulds of small mass. An increase of amplitude increased the effectiveness of compaction according to Kurt and Green, while Forssblad found it to increase the radius of action of an internal vibrator. Cusens found the velocity to be a significant variable when the frequency was kept constant, but Green suggested that this was only true because it was a function of the amplitude and acceleration. Apart from l'Hermite, few investigators have attached greater importance to frequency, although it has been generally agreed that a low frequency and high amplitude is most effective in the early stages of compaction when the concrete is loosely packed, whereas higher frequencies and lower amplitudes are better for the later stages. Saul suggested the power input as the relevant criterion, this is proportional to the square of the amplitude and the cube of the frequency."

Timms (13) provides an interesting history of the vibration consolidation of concrete pavement. He draws quite extensively on unpublished work of the Michigan Department of State Highways and concludes that careful inspection of mixing equipment, concrete materials, and vibration equipment is necessary for successful compaction of paving concrete of low slump.

4.1 INTERNAL VIBRATORS

4.1.1 Radius of Action

One of the most useful concepts regarding performance of <u>internal</u> spud-type vibrators is the "radius of action" which defines the region surrounding the vibrator within which it is effective in consolidating the concrete. A large number of variables influence this measure of effectiveness such as frequency of vibration, time during which vibrator is immersed in concrete, power of vibrator, amplitude, etc.

Figure 2 gives some data developed in Sweden (10) and shows the radius of action vs. amplitude for various frequencies and times of immersion. It is interesting to note that this data demonstrates greatest effectiveness at about 12,000 rpm whereas most American equipment operates at 8,000 to 10,000 rpm. Multiple-spud vibrators on American paving equipment are often spaced at 24 in. thus inferring a radius of action of 12 in. or slightly greater if allowance is made for overlap. At a paver speed of 10 ft/min. the time of effective immersion is then calculated to be 12 sec. The least powerful vibrator used in the Swedish study (0.6 mm amplitude as shown in Figure 2) would predict a "radius of action" of about 8 in. (20 cm) for such a time duration; thus, at least as a first approximation, American practice is viewed as reasonable in estimating the effectiveness of spud vibrators.

Reference 17 provides additional data of a similar nature and is reproduced in Figure 3. In the case of this data from Germany, the vibrators are characterized by having different eccentric moments which, for a given vibration frequency, will be proportional to the amplitude plotted in the previous figure. The German data does not demonstrate the maximum radius of action at 12,000 rpm as does the work of Forssblad in Sweden but indicates the peak to be much higher —— at perhaps 21,000 rpm. Differences in conduct of the two sets of tests were substantial. For example, the radius of action of Garbotz and Ersoy was defined as the region surrounding the vibrator in which the concrete was compacted to a density of 2.3 or greater (equivalent to greater than 143 lb/cu ft) whereas Forssblad used the criterion of extent of surface settlement. Forssblad did, however, verify

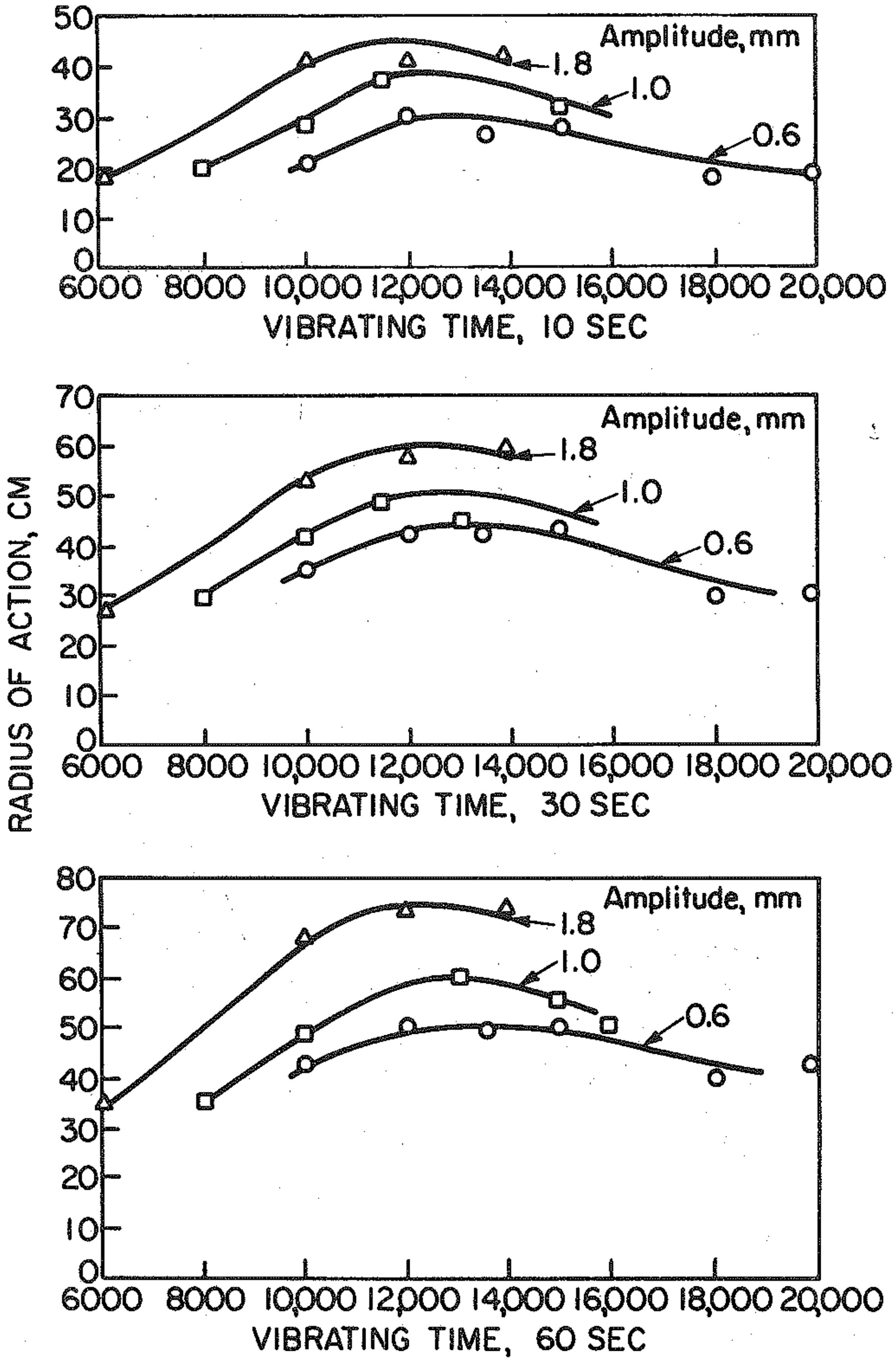
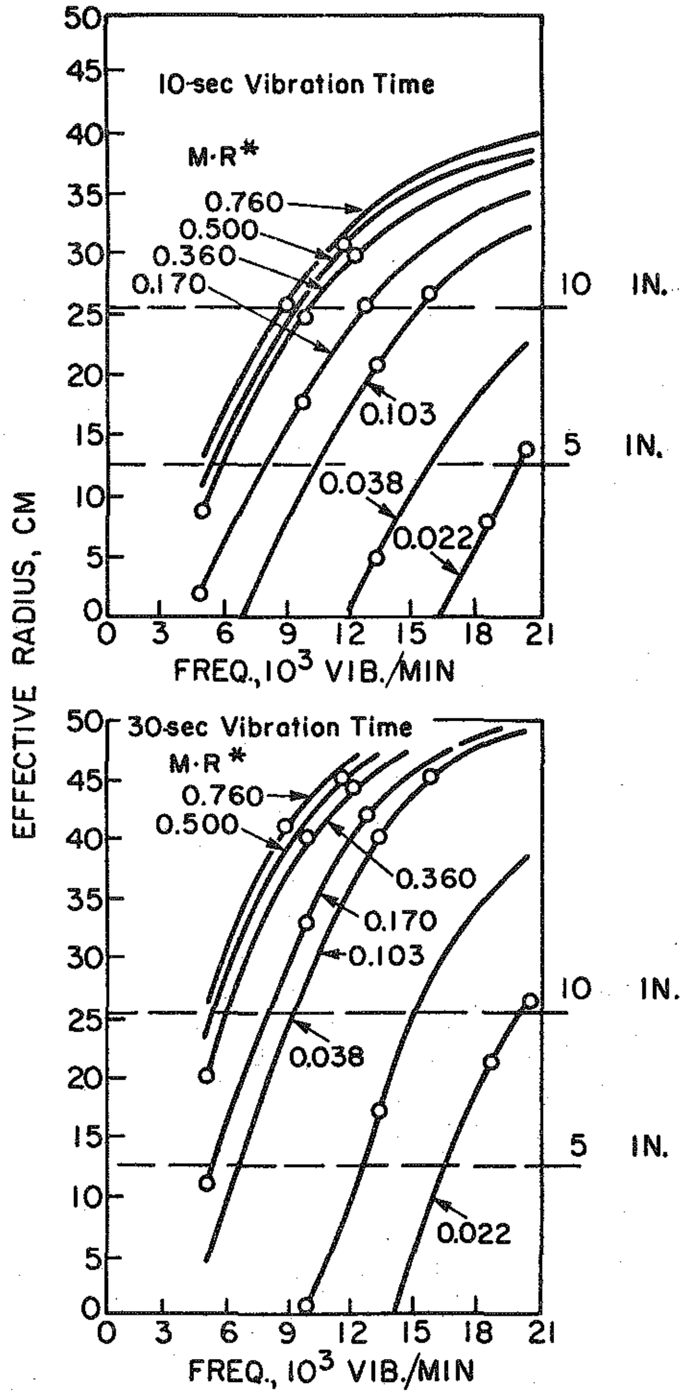


Figure 2. Radius of action as a function of frequency for three values of amplitude and vibrating time (from Forssblad (10)).



*M·R values are eccentric moments of the vibrator in metric units $\frac{gs^2}{cm}$ cm.

Figure 3. Effective radius of action as a function of vibrator force (eccentric moment) and rpm at vibration times of 10 sec and 30 sec (adapted from Ref. 17).

his reported radius in trial runs by noting the progressive decrease in sinking of steel pipes vertically placed in the concrete as distance from the vibrator increased.

In both the German and Swedish work reported above, a fairly stiff concrete estimated to have a slump of 1-2 in. was employed. Such concrete would be expected to benefit greatly from consolidation by vibration. It is common experience that the drier the mix the greater the vibration effort needed to properly consolidate the concrete. This is another way of saying that the vibrator radius of action is less for low slump mixes unless corrective measures are taken. For example, Figure 4 demonstrates that reduction in the radius of action of low-slump mixes can be remedied by longer periods of vibration. Other things being equal, this longer period of vibration could only be achieved in an actual paving operation by lowering the forward speed of the paver. Another solution is to use a more fluid, higher slump mix. Both remedies obviously have serious shortcomings. Increasing the slump is particularly undesirable since segregation of the mix can result, or a weaker concrete be provided. Higher slump may also be incompatible with need to prevent sloughing behind the paver in a slipform operation. The highly authoritative ACI Recommended Practice for Consolidation of Concrete (ACI 309-72) (3) recommends a maximum slump of 2 in. for slabs placed by vibration. Still another remedy for adequately compacting the drier mixes would be to increase the power of the vibrator so as to increase the amplitude of vibration; this remedy would be inferred from Figure 2. Reference 10 gives some data on the radius of action of an internal vibrator on a rather

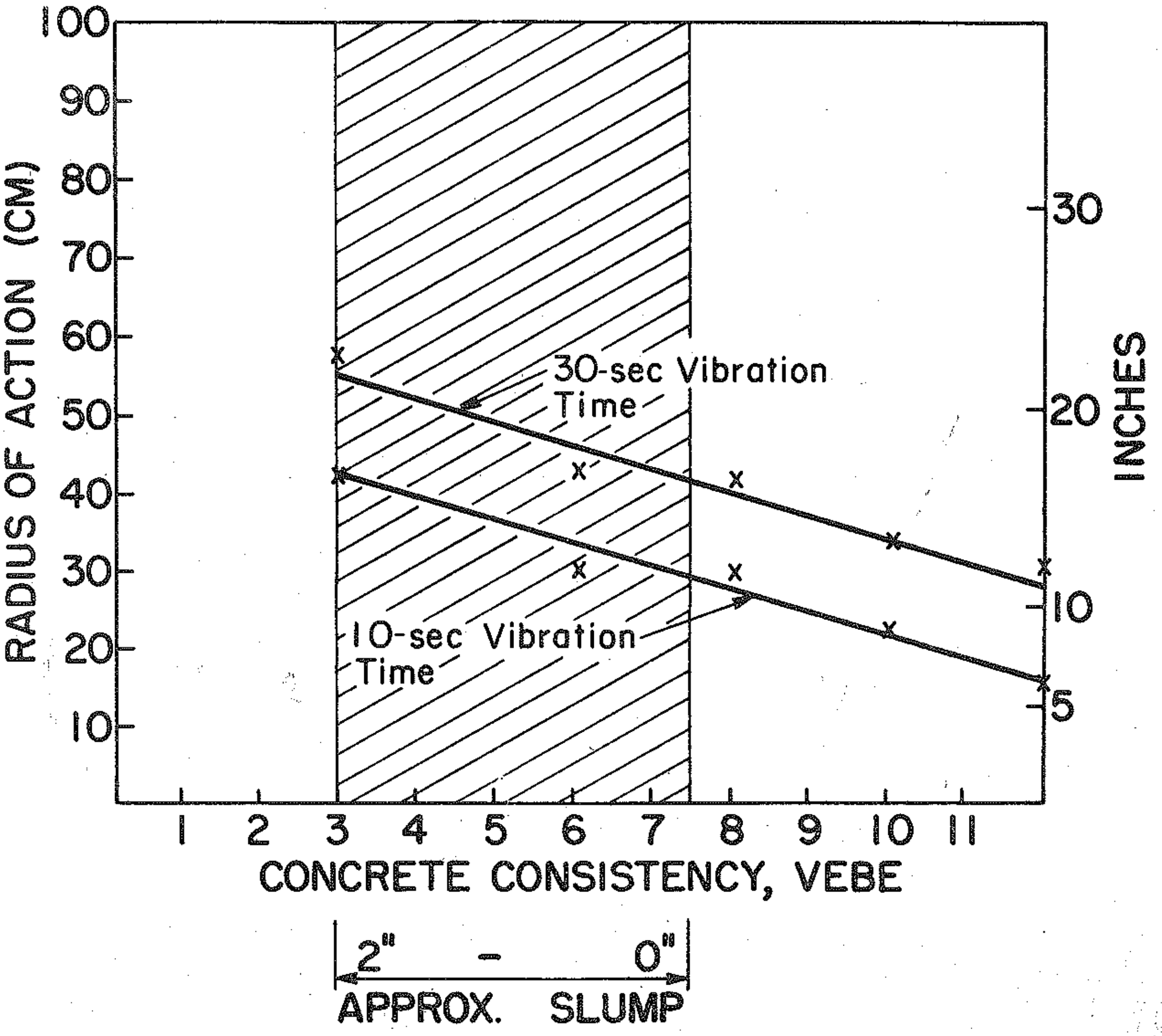


Figure 4. Radius of action of an internal vibrator vs. consistency of concrete at 10 sec and 30 sec vibration time. (Spud diameter, 2-1/2 in.; 9,500 vib/min; amplitude of vibration, 0.04 in.; from Ref. 10.)

stiff concrete vs. maximum size coarse aggregate. Figure 5 shows that at least for this one vibrator, the radius of action was greatest at about 1-1/2 in. maximum size aggregate. The radius of action was not too different for 1-in. maximum size typical of that currently used by MDSH for structural and paving work.

Figure 3 also provides data on several internal vibrators when operating at rotational speeds varying from about 5,000 to 21,000 rpm. The vibrators ranged from 1 in. to about 3 in. in diameter (size characterized on the graphs as "eccentric moment"). It is shown that an increase in frequency of the vibrator is far more effective in increasing the radius of action than is change of vibrator size. For example, halving the eccentric moment from the largest vibrator on the graph (when operating at 12,000 rpm) reduced the radius of action only about 15 percent whereas doubling the rpm's from 6,000 to 12,000 increased the radius of action about 75 percent. The Colorado data of Reference 5 likewise displays increased densification of the concrete using higher rpm's; for example, increasing rotational speed from 7,000 to 11,000 rpm increased the concrete density over 2 lb/cu ft. It seems clear that vibrator manufacturers should be encouraged to increase the rpm of their equipment and that field inspection should verify that actual rotational speed is always maintained at a sufficiently high level.

4.1.2 Power Input to Internal Vibrator

When an internal vibrator is initially thrust into stiff concrete, resistance to vibrational movement is encountered and speed of rotation is diminished as much as 1,000 rpm after which there is a gradual increase of

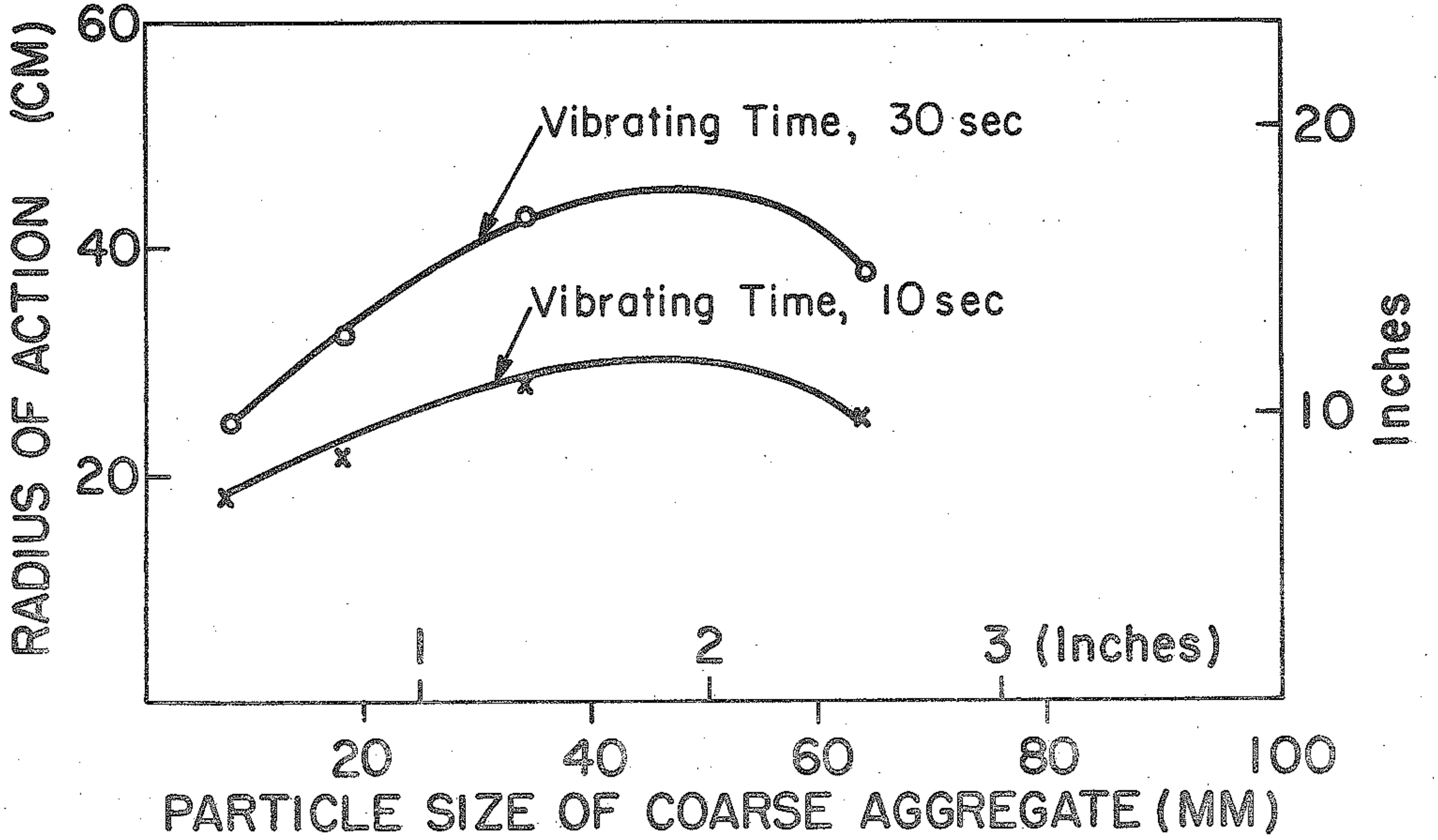


Figure 5. Radius of action of an internal vibrator vs. maximum size of coarse aggregate (from Ref. 10).

speed as particle reorientation is established. Power input to the vibrator reflects these speed changes as indicated in Figure 6; initial power input after insertion is high followed by a leveling off to an input considerably above that for free vibration in air. This feature has been considered as a possible means of monitoring vibrator effectiveness in a construction operation; i.e., over- and under- indicators could be installed on an ammeter lead to the vibrator. Unusual current consumption should indicate malfunction of the vibrator. It may still be that this approach should be followed up, however, it is not 100 percent certain that vibration effectiveness is insured even if current consumption is correct, and a more direct means of verifying proper consolidation should still be sought.

4.1.3 Table of Internal Vibrator Characteristics

Table 1 gives a useful tabulation of the characteristics of available American internal vibrators ranging in size from small 3/4 in. in diameter "pencil" vibrators used in fabrication of laboratory specimens up to vibrators suitable for consolidating large quantities of very stiff mass concrete.

4.1.4 Possible Procedures for Monitoring Field Performance of Internal Vibrators

Extensive review of the literature has revealed a wealth of information on the theory and performance of internal vibrators. There is little question regarding the ability of such equipment to accomplish good consolidation of concrete. The required sizes, rpm, spacing of insertions, and other features of proper use of vibrators are well documented, particularly so in ACI Recommended Practice for Consolidation of Concrete, ACI 309-72. The most

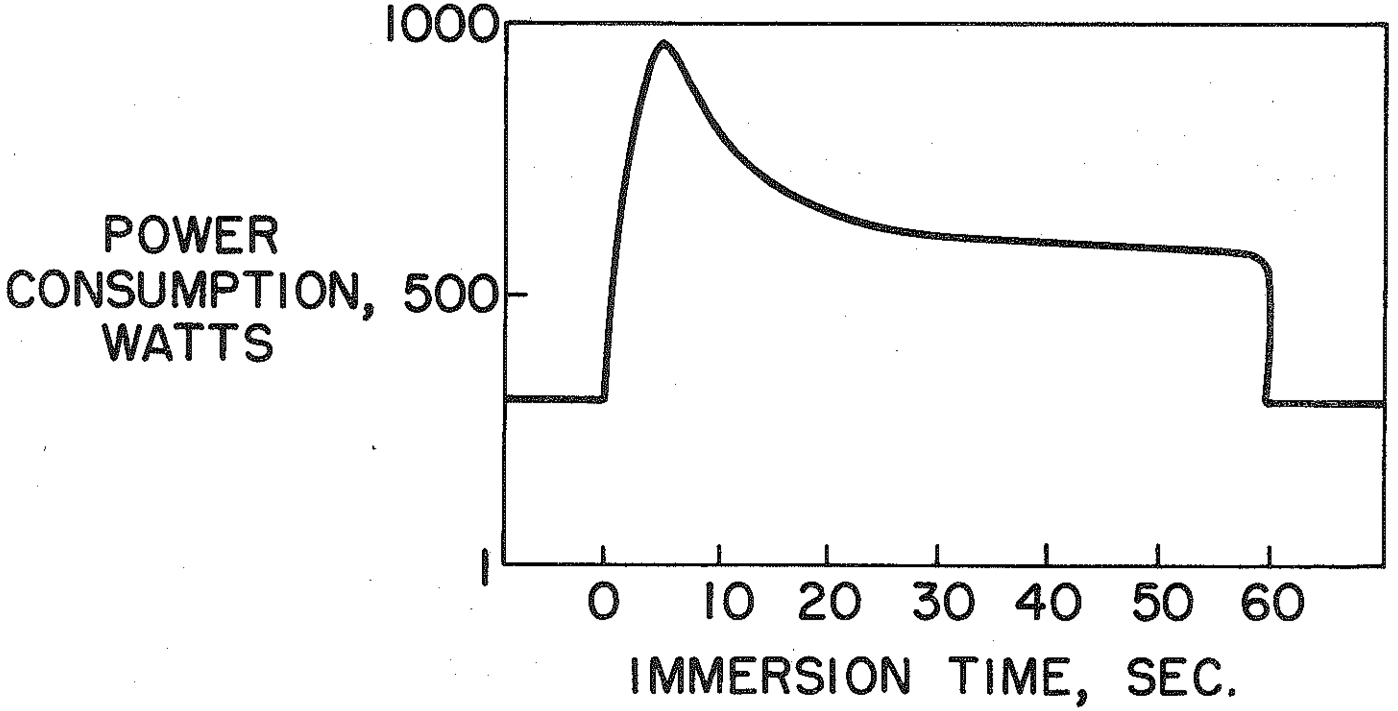


Figure 6. Power input of an internal vibrator during one immersion in concrete (from Ref. 10).

TABLE 1

RANGE OF CHARACTERISTICS, PERFORMANCE, AND APPLICATIONS OF INTERNAL VIBRATORS

(From Ref. 3)

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 (m³/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 m³) 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 m³) or more deposited at one time in the form.

Notes:

Column 3 — While vibrator is operating in concrete.

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

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

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

Column 7 — Distance over which concrete is fully consolidated.

Column 8 — Assumes insertion spacing is 1½ 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.

important shortcoming in the entire matter is inability to readily verify that the vibrators are indeed functioning properly, particularly on a high-speed paving operation using a lateral array of spud vibrators. When operating properly, the vibrators are almost entirely immersed in the fresh concrete, and there is little visual indication of whether or not they are in fact accomplishing their purpose. Several techniques have been considered as possible candidates to alleviate this deficiency, the requisites of such techniques being (a) that the technique be readily adaptable to field use both as to ruggedness and simplicity of operation, (b) that it provide information interpretable at once so that correction of any deficiency discovered can be immediately undertaken, (c) that it should not interfere in any way with the contractor's paving operations, and (d) that it should be reasonable in cost.

Below is a brief report of exploratory effort with regard to several potential techniques for monitoring performance of internal vibrators on a paving operation:

(1) Stroboscope - Several companies specializing in apparatus for timed pulsing of high-energy light were contacted. This technique has long been used for determining lack of balance of rotating machinery, speed of rotation, etc., and has the distinct advantage that physical contact with the vibrating body is not needed in order to make the measurement. However, the organizations contacted could not suggest a way in which the technique would be useful in measuring amplitude or acceleration of vibrating concrete. However, we did use strobe techniques in the laboratory very effectively for measuring frequency response of vibrators themselves. At least one organization believed

that the intensity of sunlight outdoors would make stroboscopic observation difficult.

Reference 21 reported favorably on use of strobe technique on industrial equipment where small targets ("magnifying gages") with specially scribed patterns when temporarily mounted on the machine parts and observed under strobe light would yield amplitude measurements of the order of accuracy of 20 mils (0.020 in.) at normally employed rpm's. It was envisioned that a very small lightweight disposable piece of aluminum foil inserted in the concrete surface near the vibrator might provide a target for making stroboscopic measurements. Need for the target installation puts a constraint on the technique since project personnel would thereby be alerted to the inspection underway. Appendix B lists the organizations contacted regarding strobe equipment.

(2) Holography is a very powerful new method of studying vibrations and nondestructively detecting submerged flaws in, for example, such materials as automobile tires (20). However, to our knowledge, the equipment so far developed for this work is hardly portable and is undergoing rapid change. It is not widely used, if at all, on routine analysis and is pretty much a laboratory technique at this stage.

(3) Noncontacting Electro-Optical Displacement Follower - This device combines optical and electronic principles enabling a very precise measurement of an object when vibrating at practically any frequency of interest. A beam of electrons is focused on a target attached to the vibrating object and constantly follows its movement by changing the current in beam deflecting coils.

The current required to keep the image in focus is proportional to the target displacement. This equipment is semi-portable but is very costly. Again, installation of one or more targets is necessary, and considerations similar to those adverse to use of the stroboscope arise. Furthermore, the equipment is very sophisticated and requires a competant electronics technician to keep it in operation. Two sources of this apparatus are listed in Appendix B. Only one of the two organizations still seems to be in existence.

(4) Infrared Sensors - Energy supplied to the concrete during vibration is dissipated as heat, and some thought was given to attempting to measure the resultant temperature rise remotely by infrared sensors. Equipment now available is capable of focusing to a narrow field of view and can readily detect temperature differences of about 0.5°C. Calculation reveals, however, that greater accuracy would be needed to be useful in detecting concrete surface temperature differences in the proximity of a vibrator caused by the heat generated during a vibration period of only about 12 sec.

(5) Power Input to Internal Vibrator - Section 4.1.2 gave information on a possible means of monitoring vibrator performance by measuring electrical input to the vibrator, and previous considerations will not be repeated here. However, this technique might be held in abeyance for future consideration should more direct means not appear to be feasible.

(6) Vibration Detection by Transducers - It was realized that many researches were available, as detailed previously in Section 3, wherein "after-the-fact" tests of the hardened concrete had been made which displayed the benefits of proper vibration or conversely, detriment to the hardened

concrete of inadequate compaction by vibration. However, almost from the outset of this investigation, it was postulated that the preferable means of insuring proper consolidation was by effective monitoring during the progress of construction by measuring the level of vibration impulses in the fresh concrete itself. As a consequence, several industrial firms specializing in vibration analysis, transducer design, and acoustic measurements were contacted as listed in Appendix B. Several of the respondents suggested using pick-ups of one sort or another either just contacting the surface of the concrete or slightly immersed therein in order to ascertain the magnitude and area affected by the vibration.

Validity of the concept of measuring vibrations in the fresh concrete to measure compaction effectiveness is amply supported. For example, the literature reveals that use of such techniques to measure vibrations in fresh concrete were used as early as 1938 at the U.S. National Bureau of Standards (22,23). In the meantime, advances in electronics (24) have made today's equipment much more reliable and portable, and the present report will describe in some detail tests conducted with apparatus developed specifically for this research project by Bayshore Systems Corporation, Springfield, Virginia.

Reference 17, in particular, presents unusually comprehensive data on the vibration amplitude, acceleration, and pressure in the concrete at various distances from the internal vibrator. Seven different spud vibrators were employed in the Garbotz-Ersoy work, some at three different rpm's. Probably the measurement of greatest interest is that at the limit of the "radius of action." As previously mentioned, the authors of Reference 17 defined this radius as the distance from the vibrator at which sufficient entrapped air was expelled so that the concrete attained a density of 2.3 (143 lb/cu ft).

Table 2 has been prepared using data from Reference 17. The ACI vibrator-size classifications (Table 2) are shown and the data recalculated into English units. The last three columns of the tabulation show the measured amplitude, acceleration, and dynamic pressure at the limit of the radius of action. The unusually complete data allowed these values to be interpolated. Although there is more scatter in the data than desirable, it does confirm that there is a resonably narrow response level which is to be expected at the extreme of the radius of action when measured by any of the three parameters, namely, amplitude, acceleration, or dynamic pressure. This provides encouragement that the scheme adopted in the present research should enable rapid screening of underpowered or malfunctioning internal vibrators.

The data has some perplexing aspects which need resolution. For example, there is temptation to assume simple harmonic motion of the concrete at the limit of radius of action enabling calculation of acceleration from measured amplitude, or conversely, amplitude from measured acceleration. Such calculation occasionally leads to large discrepancies between measured and calculated values, sometimes as much as a factor of ten. Resonance effects or departure from sinusoidal motion may cause such discrepancies. Present work did not aid resolution of these discrepancies.

4.2 SURFACE VIBRATORS

As early as 1937, extensive work was reported in consolidating paving concrete using vibrators either mounted on screeds riding on the surface of the concrete or inside tubes spanning the full width of the pavement immediately

TABLE 2

MEASURED OPERATING CHARACTERISTICS OF SEVEN INTERNAL VIBRATORS—10-SECOND VIBRATION TIME

(Data interpolated from Ref. 17)

ACI Group Class	Dimensions of Vibrator Head, in.		Radius of Action, in.	Eccentric Moment, in./lb	Frequency of Vibration, vib/min	Measured Vibration at Limit of Radius of Action		
	Diameter	Length				Amplitude, in.	Acceleration, g's	Dynamic Pressure, psi
*	1-1/4	15	2-3/8	0.025	18,600	0.0010	3.5	1.92
*	1-1/4	15	5-1/8	0.025	20,400	0.0009	2.4	0.94
1	1	9-1/2	2	0.045	13,200	0.0008	3.3	1.32
2	2	12-1/2	8	0.121	13,200	0.0028	1.1	1.66
2	2	12-1/2	10	0.121	15,600	0.0011	2.6	2.20
3	1-3/8	13-3/4	3/4	0.200	4,800	0.0011	1.1	--
3	1-3/8	13-3/4	7	0.200	9,600	0.0012	2.2	1.42
3	1-3/8	13-3/4	10	0.200	12,600	0.0020	0.4	2.42
3	2	10	3	0.424	4,800	0.0013	0.7	1.83
3	2	10	9-1/2	0.424	9,600	0.0028	1.8	1.74
3	2	10	11-3/4	0.424	12,000	0.0041	2.0	1.35
3	3	25-1/2	12-1/4	0.588	11,400	0.0019	3.0	2.74
4	3	25	10-1/4	0.894	8,700	0.0043	3.1	3.83

*Below ACI vibrator eccentric moment size classification.

Note: All measurements at 10-sec vibration time.

under the surface and just ahead of strike-off (14,15). Reference 15, in particular, describes use of an 18-in. wide vibrating shoe screed much like those used today in some installations. In those days there seemed to be much preoccupation with the economies afforded by vibration placement of paving concrete wherein use of a lower slump enabled reduction of cement without sacrifice of strength.

Use of vibratory screeds to aid strike-off has been widespread in slab work such as bridge deck placement; the advantages of such are immediately evident by the ease with which a well-shaped and smooth surface is achieved. The extent of consolidation provided deeper down in the slab by such equipment has not been as extensively investigated. However, the Road Research Laboratory in England did undertake such a study in the late 1940's (6,8,24).

The British work used outdoor semi-full scale slabs, 18 ft long by 4 ft wide by 18 in. deep. This was an unusually comprehensive research and many variables were studied. Quoted below is a summary of their findings:

> "Conclusions - The experimental vibrating machine has been used to study the effect on the compaction of concrete slabs 18 in. thick of varying the frequency of vibration between 1,500 and 6,000 v.p.m., the acceleration between 1 g and 12 g, the amplitude between 0.004 in. and 0.06 in., and the forward speed of travel between 1 and 8 ft per min; a rectangular shoe was fitted to the vibrating beam throughout the main series of experiments. The following conclusions may be drawn:
>
> (a) When the vibrator was operated at constant acceleration and constant number of vibrations per foot of travel, increase of the amplitude of the beam (which was, of course, accompanied by decrease of frequency) increased the depth of compaction.
>
> (b) At constant acceleration and amplitude of the beam, slower speeds of travel (i.e., increase of number of vibrations per foot run) increased the depth of compaction.

(c) When both the amplitude of the beam and the number of vibrations per foot run were fixed, the depth of compaction was independent of the acceleration of the vibrator beam.

(d) The density attained at a given depth in the concrete was dependent on the peak value of the particle velocity attained at that depth.

(e) The density attained at a given depth in the concrete depended on the total work done on a particle at that depth.

(f) For the concrete employed in these tests, the depth of compaction increased with the total movement which could be transmitted by the beam, i.e., with the amplitude of the beam multiplied by the number of vibrations per foot run. The depth of compaction in a thick slab attained a limiting value at approximately 12 in.

(g) Since the design of a vibrator is usually based on a fixed value of acceleration, it would appear that the best compaction would be obtained with a vibrator having a large amplitude and low frequency. This should also result in economy in design.

(h) The best surface finish was obtained at high frequencies of vibration, the high frequencies tending to produce a 'sandpaper' finish while low frequencies left some parts of the surface unsealed."

It should be pointed out that the concrete used in the above work was of stiff consistency (compacting factor 0.80, equivalent to no slump) which undoubtedly has a bearing on inability to achieve compaction of slabs at depths greater than 12 in. The British authors' views regarding advantages of low-frequency, high-amplitude compaction is not shared by most investigators of <u>internal</u> vibration. Initial "melt-down" is achieved by low-frequency vibration but subsequent fluidizing and dispelling of gross air voids is not readily accomplished. In fact, the concrete densities achieved by the British authors as previously displayed in Figure 1 are disturbingly poor for consideration as optimum compaction.

Another feature of surface consolidation which can be easily overlooked is the need for a surcharge not only to replenish concrete consumed by densification but to exert a static head. Maintenance of a uniform "roll" ahead of the vibrating screed or pan insures intimate contact and transfer of vibrational energy to the concrete; any gaps or bridging of the screed indicate there are areas receiving improper vibration. A steel plate placed on the concrete was helpful in concrete being revibrated from underneath as reported by Hilsdorf, _et_ _al_., in Reference 25. In the latter case, the plate was apparently effective as a reflector to prevent escape of the vibrational energy from the specimens.

All things considered, it seems appropriate that a vibrating screed or pan should be viewed as an aid to surface shaping or smoothing but not as very efficient in achieving internal consolidation.

4.3 FORM VIBRATORS

Although not of immediate interest to this investigation, much excellent research has been done in the past on external vibrators as typically used in the precast industry (2,12,26). A great many variables have been studied and as is the case with much vibration work, some anomalous results have been reported.

One of the most interesting aspects of external vibration is that of the possibility of a special type of "over-vibration," even of very dry mixes, wherein "rotational instability" is established caused by so much high frequency energy being fed into the concrete that instead of being compacted it actually undergoes a slow rotational movement in the form. Plowman in Great Britain particularly reported on this phenomenon (26).

Bennett and Gokhale (12) performed some experiments which established certain advantages for external vibration using a combination of two vibration frequencies — one fairly low and one high. The literature contains quite a number of observations that initial consolidation is aided by low-frequency, high-amplitude vibration, whereas final compaction to drive off entrapped air is favored by high-frequency, small-amplitude vibration. The authors sought to provide both simultaneously and with some success but did not make field trials.

The present investigation has given considerable attention to the researches involving external vibration, but whether or not the findings are applicable to internal or surface pan vibration has not been proved. External form vibration differs greatly in that the entire body of the concrete is caused to vibrate—at least such vibration aims to accomplish this—whereas internal vibration, in particular, aims to radiate the vibrational energy out from a source either by particle to particle contact or more likely by transmitting pressure waves through the liquid phase. It is our judgment that the study of the latter type of vibration has many more uncertainties.

5. ACOUSTIC MONITORING OF VIBRATORS IN FRESH CONCRETE

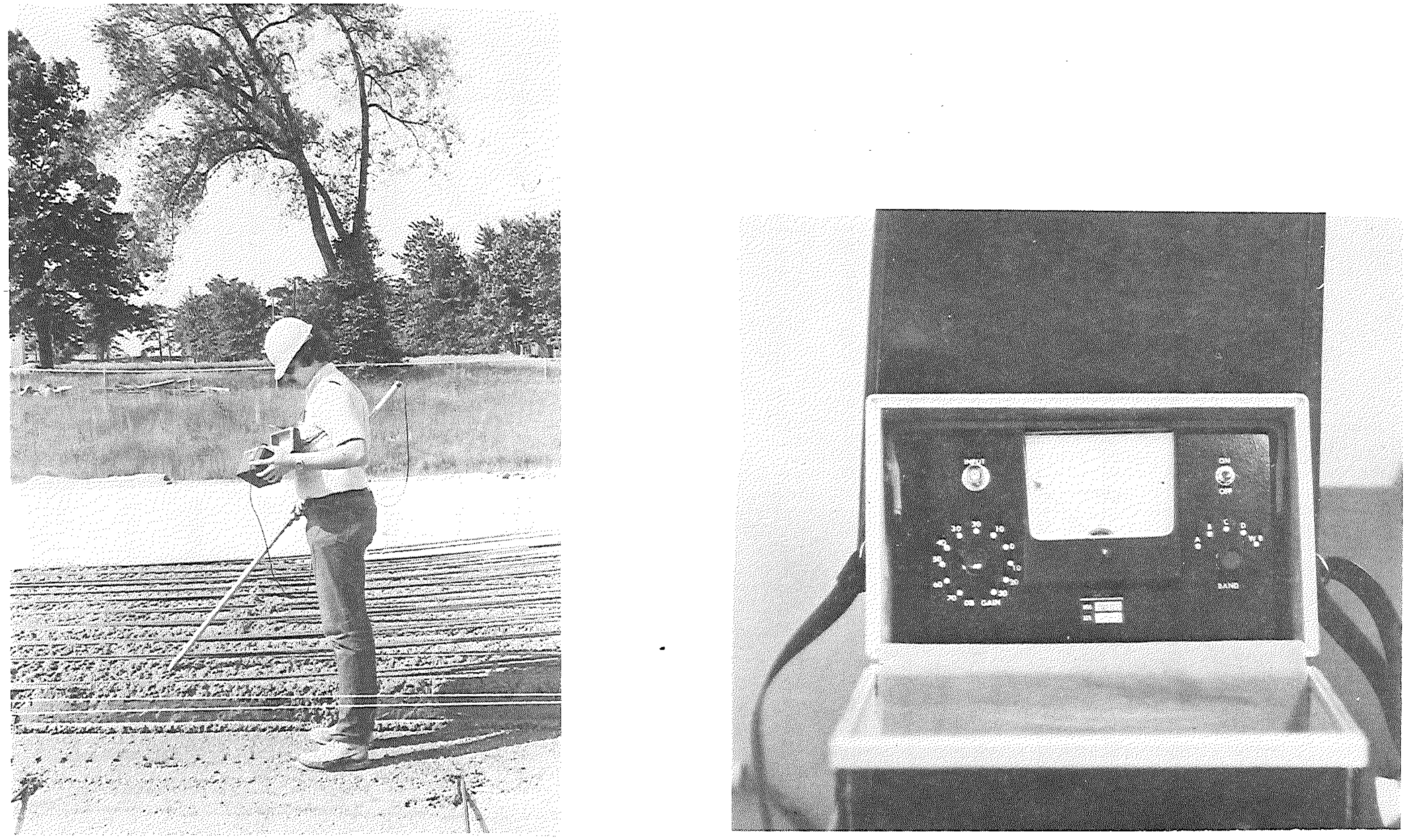
5.1 INSTRUMENTATION

Study of previous work on vibration consolidation of fresh concrete revealed the liklihood that present advances in electronics would permit design of a reliable system in which a detector could be momentarily inserted in the fresh concrete and the electrical output be quickly analyzed both for vibration frequency (rpm) and for pressure or energy level. In this way, the compaction energy being supplied the concrete at the place of insertion of the detector could be assessed, and with knowledge of the degree of compaction being acheived, a background of information would be gathered for comparison purposes.

Field trials of the designed instrument have been conducted but are presently insufficient in amount to fully substantiate the proposed inspection scheme.

The instrument consists of a ceramic hydrophone mounted in the end of a 6-ft hollow metal rod (1-1/8 in. O.D.) providing a convenient means for reaching fairly inaccessible vibrator locations near present-day paving machines. A 9-ft lead wire from the other end of the rod is connected to a control box. The latter is 7 in. long, 4-1/2 in. wide, and 4 in. high and weighs 1210 g (about 2-1/2 lb). It has been found convenient to keep the control box in a leather camera case with shoulder strap (Figure 7).

The control box has an on-off switch, dial meter with full scale reading of 10 divisions subdivided in 0.2 divisions, and two multiple position switches which control sensitivity and frequency response range, respectively. Five frequencies may be selected as follows:



(a) Acoustic probe inserted in concrete and signal being read on control box.

(b) Close-up of control box in carrying case.

Figure 7. Acoustic probe for measuring vibration compaction of fresh concrete.

Band A - 50 to 80 Hz (3,000 to 4,800 rpm)

Band B - 80 to 120 Hz (4,800 to 7,200 rpm)

Band C - 120 to 160 Hz (7,200 to 9,600 rpm)

Band D - 160 to 200 Hz (9,600 to 12,000 rpm)

Band WB - 20 Hz to 7 KHz (1,200 to 420,000 rpm)

After insertion of the detector in the concrete, the approximate frequency being furnished by the particular vibrator is easily determined by switching through the positions to find the Band giving maximum response on the meter. So far, field trials have revealed paving equipment vibrating in the B, C, and D frequency bands.

The "DB Gain" switch has 10 positions corresponding to an overall 100-decibel change of sound pressure. The logarithmic compression of the decibel system allows covering a very large range of sound pressures. For this instrument,

$$DB = 20 \log_{10} \frac{P}{P_o}$$

where; P_o = 1 microbar (approximately one millionth atmosphere)

With a full scale reading of 10 on the 70-DB scale, computation reveals that the dynamic pressure should be 31,620 microbars (equivalent to about 0.45 psi).

Battery drain on the control box is very small since solidstate components are used throughout; the two disposable 9-volt portable radio batteries are estimated to provide 30-hr operation.

The instrument was designed and constructed by Bayshore Systems Corporation, 5406A Port Royal Road, Springfield, VA 22151 and cost $790.

Experience with the instrument so far reveals it to be rugged and reliable and well suited to its purpose. We would suggest only very minor modifications in subsequent models to make it easier to use.

5.2 FIELD TRIALS WITH BAYSHORE VIBRATION DETECTOR

Due to various delays, including a work stoppage on concrete paving jobs, field trials of the Bayshore euqipment have not been as extensive as desired, but the results obtained on four different construction projects are reported in Table 3 and give considerable encouragement for the system.

It is observed in the tabulation that Projects 1 and 4 used modern slip-form equipment which requires very uniform concrete of low slump in order to maximize production efficiency. The spud vibrators on these two projects could be visually observed to successfully "fluidize" the concrete and gave good pressure levels on the Bayshore meter as well as reasonably high frequencies of 9,000 to 9,500 rpm.

Project 2 in the table used old equipment requiring fairly high slump concrete to accomplish placement. The two low-frequency spud vibrators near the side forms did not register a very high sound pressure, and formation of surface sheen adjacent to the vibrators was not apparent, or was masked by the already fluid concrete.

Project personnel on Project 3 decided that the normally required spud vibrators adjacent to the sides of the forms were not needed since honeycomb was not evident on the vertical faces of the slab edges. Decision was made that the vibrating mesh depressor was providing sufficient energy to accomplish compaction. The low vibrating frequency of the depressor and relatively weak

TABLE 3

BAYSHORE ACOUSTICAL METER FREQUENCY AND SOUND PRESSURE MEASUREMENTS ON PAVING PROJECTS

Project:	1	2	3	4
Contractor:	Denton	Denton	Eisenhour	Eisenhour
Location:	On I-96 relocated just east of I-275 interchange northeast of Plymouth	On I-275 at Schoolcraft northeast of Plymouth	On I-96 relocated just east of Grand River Avenue	On SB US-127 2 mi north of Lake Lansing Road, northeast of Lansing
Type of Construction:	12-ft lane slipform, continuously reinforced	12-ft lane, formed, conventional mesh reinforcement	24-ft lane, formed continuously reinforced with mats	24-ft slipformed continuously reinforced
Paver and Vibrators:	Rex - 6 spuds	--- 2 spuds, each about 18 in. in from form	Helzel flexplane vibrating mesh depressor only	CMI slipform 11 spuds
Vibrator Frequency, rpm:	9,500	4,500 left 4,000 right*	2,500	9,000
Sound Pressure, Scale Reading:	52-54 at vibrators 41-48 at 1 ft away	34 at 6 in.	55 in contact with mat 25-34 between bars	53-58 at vibrators 36-45 1 ft away
Paver Speed, ft/min:	9	---	---	12

*Became inoperative during inspection and was replaced with small Stow vibrator at 10,000 rpm, giving 50 sound pressure scale reading about 6 in. away.

sound pressure measured between the meshes of the reinforcement gives cause to speculate that the concrete may already have been fluid enough to not require much, if any, vibration for proper consolidation. Project personnel stated the slump averaged 2 to 2-3/4 in. It should be realized that the mesh depressor blades provide very small cross-sectional area to the concrete in the direction of their vibration, and transfer of much vibrational energy cannot be expected.

6. CONCLUSIONS

1. Consolidation of paving concrete of less than 3-in. slump will be improved by vibration. In fact, it is mandatory that concrete placed by slipform be vibrated since it is necessarily of drier consistency and therefore requires greater energy input for proper consolidation. Proper consolidation of paving concrete implies that it has been vigorously manipulated so as to make intimate contact with the underlying base at all points and that the majority of entrapped air voids have been dispelled.

2. Several techniques have been tried by different investigators to evaluate by examination of the hardened concrete that good consolidation has been accomplished; these include unit weight determinations of drilled cores, visual examination for general honeycomb or, particularly, for porosity at bottom end of core, strength tests, ultrasonic pulse velocity determinations, etc. All of these "after the fact" methods suffer from one serious shortcoming namely, that remedies can be undertaken only on subsequent production.

3. There is obvious need for a rapid field method for determining that proper vibration consolidation is being acheived.

4. Vibration in the fresh concrete can conceivably be characterized by measurement of several possible parameters such as frequency of vibration, duration, amplitude of pressure waves, particle acceleration, etc.

5. In turn, response of a given concrete to these parameters depends upon a number of factors such as location and type of vibrator (internal spud, surface pan, vibrating screed, etc.)

6. Also, concrete characteristics such as slump, mix proportions, and

aggregate grading govern response of the concrete to vibration. Temperature and delay after mixing also have influence.

7. Study of the literature tends to show that vibration frequencies higher than often employed, or specified, have great advantage in properly consolidating concrete. A minimum frequency of 150 Hz (9,000 rpm) is suggested as a reasonable goal.

8. Close examination of fairly extensive researches reveals that pan vibrators or vibrating screeds serve well for strike-off and surface consolidation of concrete but are not very effective deeper down in the mass in dispelling entrapped air voids. It is suggested that use of such equipment be optional with the paving contractor and not be considered as an acceptable substitute for required internal vibrators.

9. A useful concept regarding internal vibrators is the "radius of action" which is the region surrounding the vibrator within which adequate consolidation is being acheived.

10. A number of candidate procedures for field monitoring the magnitude of this radius of action of specific vibrators were considered such as strobe techniques, holography, electro-optical displacement follower, etc.

11. The method of monitoring vibrator performance proposed by this research is that of using acoustical techniques wherein both vibrator frequency and sound pressure are rapidly evaluated by insertion of a probe in the concrete, the end of which contains a hydrophone. The signal is quickly measured with a portable control box. Field trials with this equipment which was designed by Bayshore Systems Corporation, Springfield, Va. are very encouraging.

12. Admittedly limited field trials suggest, as a first estimate, that

if all points in the slab receive at least 10 sec of vibration of 9,000 rpm, or greater, with a Bayshore instrument scale reading of 35, or greater, the slab should be adequately consolidated.

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APPENDIX A

VIBRATOR HARMONIC MOTION

(From Ref. 3)

An eccentric having weight, w, rotating inside the vibrator head causes the head to revolve in an orbit, any point on the casing follows a circular path whose radius is the amplitude of the vibrator.

Referring to Figure 1A, the random point, M, on the vibrator spud has the following vertical displacement at time, t:

$$y = a \sin 2\pi nt$$

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

and: $n = 1/T$ = frequency, cycles/sec (Hz)

a = amplitude, deviation from point of rest, in. (cm) (Note that this is 1/2 peak-to-peak amplitude.)

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

$$g\text{'s} = \frac{4\pi^2 n^2 a}{g} =$$ maximum acceleration expressed in terms of acceleration of gravity, g.

where g is 386 in./sec^2 or (981 cm/sec^2)

Figure 2A is a schematic view of the action of a rotary eccentric where:

W = weight of shell and other non-movable 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)

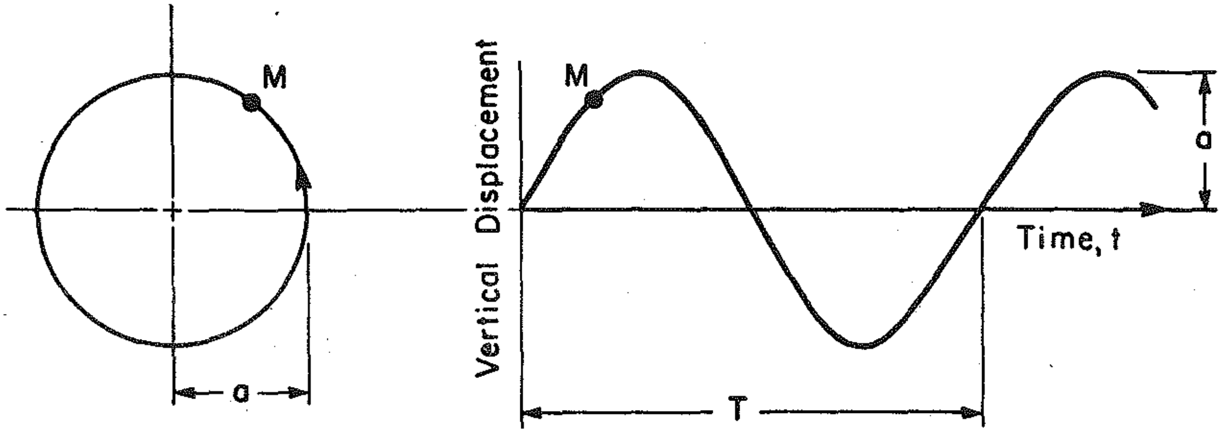

Figure 1A. Sinusoidal displacement of particle M.

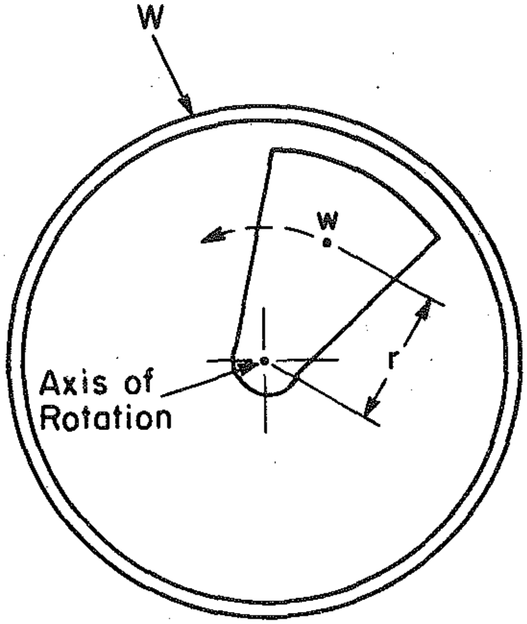

Figure 2A. Rotation of eccentric in vibrator.

wr = eccentric moment, in.-lb (cm-kg)

$F = (w/g)4\pi^2n^2r$ = centrifugal force, lb (kgf)

$a = \frac{wr}{W + w}$ = computed average amplitude, in. (cm)

Elements of the concrete not in immediate contact with the vibrator are, of course, not undergoing orbital motion but are subject to compressional waves, whose amplitude rapidly diminish as distance away from the vibrator increases. The latter attenuation of the vibrator effect has been the subject of much research and is covered more completely in the main text of this report.

APPENDIX B

COMMERCIAL SOURCES OF VIBRATION EQUIPMENT

Potential Sources of Stroboscopes

*Photostress Corporation
101 Geiger Road
Philadelphia, Pennsylvania 19115

*B & K Instruments
511 West 164 Street
Cleveland, Ohio 44142

EG & G, Inc.
35 Congress Street
Salem, Massachusetts 01970

*General Radio
300 Baker Avenue
Concord, Maryland 01742

General Radio
3300 South Dixie Drive
Dayton, Ohio 45439

**Chadwick-Helmuth
111 East Railroad Avenue
Monrovia, California 91016

**Sargent-Welch
7300 North Linder Avenue
Skokie, Illinois 60067

Potential Sources for Noncontacting Electro-Optical Displacement Measurement Systems

Optron
30 Hazel Terrace
Woodbridge, Connecticut 06525

Physitech, Inc.
Willow Grove, Pennsylvania, 19090

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*Recommended another system for measurement.

**Could not provide or would not recommend their equipment for such use.

Potential Sources for Transducer Systems

Tiby Company
2245 Warrensville Center Road
Cleveland, Ohio 44118

Hewlett-Packard
1501 Page Mill Road
Palo Alto, California 94304

General Radio
300 Baker Avenue
Concord, Maryland 01742

B & K Instruments
411 West 164 Street
Cleveland, Ohio 44142

IRD Mechanalysis
6150 Huntley Road
Columbus, Ohio 43229

Bayshore Systems Corporation
5406A Port Royal Road
Springfield, Virginia 22151

General Radio
3300 South Dixie Drive
Dayton, Ohio 45439