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16. Abstract

An extensive literature review of current consolidation practices and a laboratory investigation to determine the effects of coarse aggregate factor, maximum aggregate size, vibrator spacing, the method of vibrator mounting, and the use of superplasticizers with and without set retarders on the achieved consolidation of continously reinforced concrete pavement (CRCP) were performed. Also studied were variations in consolidation throughout the depth of CRCP slabs and a new technique utilizing acceleration as a method of monitoring the consolidation progress in the fresh concrete. The consolidation varies throughout the depth of concrete slabs with the greatest density existing in the bottom. For the aggregate gradations used, a maximum coarse aggregate factor of 0.80 and a maximum aggregate size of 1-1/2 inch yielded the best consolidation. Mounting vibrators perpendicular to the direction of travel was not found to be as effective as a parallel mounting method and superplasticizers were found to have detrimental effects on consolidation of stiff concrete. The measurements of acceleration were found to be a viable method of monitoring the consolidation process in fresh concrete.

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METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.6	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha

MASS (weight)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	

MASS (weight)

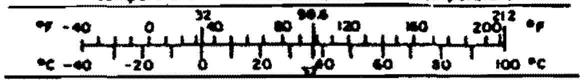
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	36	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³

TEMPERATURE (exact)

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONSOLIDATION OF CONCRETE PAVEMENT

by

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DISCLAIMER

The information contained herein was developed on Research Study 2-8-83-341 titled "Consolidation of Concrete Pavement" in a cooperative research program with the Texas State Department of Highways and Public Transportation and the U.S. Department of Transportation, Federal Highway Administration.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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SUMMARY AND IMPLEMENTATION

Due to concern for the need to develop better methods of densifying continuously reinforced concrete pavements (CRCP), an extensive literature review of current consolidation practices and a laboratory investigation to determine the effects of coarse aggregate factor, maximum aggregate size, vibrator spacing, the method of vibrator mounting, and the use of superplasticizers with and without set retarders on the achieved consolidation of CRCP were performed. Also studied were variations in consolidation throughout the depth of CRCP slabs and acceleration as a method of monitoring the consolidation process.

The laboratory investigation consisted of batching sidewalk-sized CRCP slabs, and each test was given the same vibratory effort. Analysis was made on cores taken from the slabs for the relation of splitting tensile strength, to give reference to the resulting strength of the concrete, vs. void content, to determine the degree of consolidation achieved. Because consolidation was found to vary throughout the depth of the slabs, the cores were sectioned so that a separate analysis could be conducted for both the top and bottom of the slabs.

The results of the study revealed that a maximum coarse aggregate factor of 0.80, a maximum aggregate size of 1-1/2 in., and a maximum vibrator spacing of 24 in. should be specified when slip-form paving CRCP. Mounting vibrators perpendicular to the direction of travel was not found to be as effective as a parallel mounting method, and superplasticizers were found to have detrimental effects on consolidation. The slabs were found to be more dense in the bottom than in the top, and acceleration measurements were found to be a valuable method of monitoring consolidation as it occurs.

A prototype Vibrator Monitoring System (VMS) has been developed. This system can monitor a total of 15 vibrators simultaniously and detect if one or more vibrators are not functioning properly and when liquefaction in the fresh concrete has taken place (Appendix H). This system is ready to be field tested by the Department. A first generation single sensor VMS was tested in a project on State Highway 288 in Houston. Based on this field test, strengthening of the sensors and wiring as well as minor modifications to the alarm system has been incorporated into the latest VMS.

Further research should be conducted to find a method of determining the consolidation of extremely honey-combed concrete, to further the use of acceleration measurement as a control of consolidation, to determine if guidelines can be developed whereby plasticizing admixtures can be used to increase the strength of CRCP while maintaining the void content, and to advance the understanding of the effects of mounting paving vibrators perpendicular to the direction of travel.

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CHAPTER I

INTRODUCTION TO THE PROBLEM

Definition of the Problem

According to the Texas State Department of Highways and Public Transportation (SDHPT), there is immediate concern for the inadequacies of current construction methods to properly consolidate concrete pavements. The problem appears to be more prevalent in continuously reinforced concrete pavements (CRCP) where slip-form pavers are used. The slip-form pavers require a very low slump concrete, and it is apparently difficult to achieve adequate consolidation beneath the heavy mats of reinforcing steel.

Presently, the specification being utilized by the SDHPT in the construction of CRCP is found in Item 366 "Concrete Pavement (Continuously Reinforced)" of the Texas Highway Department's "Standard Specifications for Construction of Highways, Streets and Bridges" (1).

Objective of This Study

This study was designed to examine the current state-of-the-art in vibrating freshly placed CRCP concrete and develop procedures and guidelines whereby the optimum consolidation of CRCP can be achieved.

Scope of This Study

This study consisted of extensive research into the theory and principles of consolidation by internal vibration, a determination of the present state-of-the-art regarding the consolidation of CRCP by internal vibration, and a laboratory investigation of certain test parameters to determine their effect on the achieved consolidation of CRCP.

The test parameters chosen for study in the laboratory investigation included: (1) coarse aggregate factor; (2) maximum allowable coarse aggregate size; (3) spacing of the paving vibrators; (4) method of mounting the paving vibrators; (5) superplasticizers with and without set retarders; (6) analysis of variations in consolidation through the depth of the CRCP slab; and (7) acceleration measurement as a method of monitoring consolidation by vibration. Each of these parameters of study are discussed in detail in the following Chapters.

CHAPTER II

LITERATURE REVIEW

Background Description of Consolidation

Consolidation is defined as a purposeful action taken to remove the entrapped air from a freshly placed hydraulic-cement concrete mixture (2). A mass of fresh concrete, when initially placed in a form or mold, contains air voids, primarily entrapped air, and usually does not conform intimately to the shape of the form and to the reinforcement. Since strength, durability, bond to the reinforcement, deformation, and appearance of surfaces are all closely related to the denseness of the concrete, it is both necessary and economical to do work on the concrete mass to remove most of the entrapped air (3).

Today, most concrete is consolidated by vibration. Vibration subjects the fresh concrete to very rapid impulses which temporarily liquify the mixture and cause the concrete level to subside (slump). The entrapped air, being the lightest in the mix, rises to the surface where it escapes (4). Vibration per se does not improve the properties of concrete; however, it removes large air 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 (2).

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, therefore densifying the mass (2,5). Popovics has suggested that the shape of the coarse aggregate particles is of decisive importance during this stage (2). 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 (2,5). The mortar still contains numerous entrapped air bubbles as large as 1 in. and amounting to several percent by volume of the concrete (2,5).

In the second stage of consolidation, the mortar assumes the major role of transmitting pressure waves more efficiently (2). This causes the entrapped air to rise to the surface and escape. Because of their greater buoyancy, larger bubbles are more easily removed than smaller ones (2). Air voids near the vibrator are released before those further away from the vibrator, near the fringes of the radius of action. There is also some indication that vibration itself creates small bubbles, probably by dividing larger ones (2). The removal of voids 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 air voids (2).

Consolidation imparts many benefits upon the properties of the concrete:

1. It reduces the undesirable air voids (entrapped air).

2. It allows for a lower water content of the mix (6).

3. It reduces the permeability of the hardened concrete (2).

4. It increases the bonding to and reduces the corrosion of the reinforcement (6,7,8).

5. It reduces drying shrinkage (6).

6. It increases freeze/thaw resistance (even if some air-entrained voids are removed) (2).

7. It is mandatory at construction joints or where there is a congestion of

reinforcing steel (2).

Since internal vibration is the most popular means of mechanical consolidation, an understanding of the internal vibrator is imperative. An internal vibrator consists of a head containing an unbalanced weight (eccentric) which is driven by a motor and caused to rotate at very high speeds (4,9). The forces transmitted to the concrete during vibration act at right angles to the head of the vibrator. An internal vibrator must efficiently consolidate the concrete mixes used on the job. It should be chosen by its head diameter (based on the size of the coarse aggregate, slump, and desired radius of action), frequency (which determines the liquefaction of the concrete), and amplitude (which determines the radius of action) (4,5). Consideration should also be made of the centrifugal force and the horsepower of the motor (4).

State-of-the-Art for Internal Vibration of CRCP

In an effort to determine the state-of-the-art in research of CRCP consolidation, an extensive literature review was conducted. With the aid of the Texas A&M University Library, searches were made using the Highway Research Information Service (HRIS), the National Technical Information Service (NTIS), the Geodex System-S, and a review of the card catalogues. These searches provided over 200 possible references pertaining to the topic of consolidation. Of these 200 references, 67 were located and secured. About 20 of these 67 references provided valuable information that was used in the literature review. Information from the other references was either non-applicable to this particular subject, or served only to restate or reinforce what was included in other sources.

A review of the literature concerning the study of CRCP consolidation reveals a considerable amount of information on the subject. Recent years have seen an influx of numerous studies aimed at finding ways to improve the consolidation process. While the amount of research has been quite extensive, there still remain very serious problems that need immediate attention. The following paragraphs give a short review of the most current agreed-upon facts regarding the consolidation of CRCP.

Researchers have found that vibrator spacing on gang-mounted paving machines is a function of the radius of action, which is determined by head size, frequency, acceleration, type of reinforcement, vibration time, and degree of consolidation required (2,4,10,11). Vibrators are typically spaced from 14 to 24 in., resulting in 97 percent consolidation based on rodded unit weight (AASHTO T121) (2,4,10,11,12). Air entrainment has not been found to be substantially affected by the level of consolidation, and the benefits attained by adding air entrainment remain intact (2,11,13).

Aggregate size, shape, and uniformity have been found to influence the percentage of entrapped air voids for a given level of consolidation (10,14). No research could be found regarding a variation of the coarse aggregate factor and its subsequent effect on consolidation. Frequency of the internal vibrators, while in fresh concrete, should be maintained between 8,000 and 12,000 vpm with an optimum level at 10,800 vpm (2,4,11,12,13,15,16,17,18). The amplitude in air should be held between 0.025 and 0.050 in. (4,12).

Acceleration is the cause for the loss of internal friction during vibration, but there seems to be no accepted level of acceleration for achieving optimum consolidation (13). The ACI Committee 309 reports that for a water-cement ratio of 0.40 the compaction effect increases linearly when the acceleration is increased from 9.8 to 39.2 m/sec^2 (1 to 4 g's) (10). Further increases in acceleration do not aid consolidation (10). For more information on acceleration and its role in the consolidation process see the section in this Chapter entitled "Consolidation vs Acceleration".

Slump must be maintained in the range of 1 to 2-1/4 in. and optimally should lie between 1-1/2 and 2 in. (2,11,12,13,15,16,19). Segregation has been found to be of little concern during even prolonged periods of vibration on stiff mixes, but if it should become critical, then a lowering of the slump value is recommended (20). Continued vibration has been determined to have very little effect on strength, other than directly in the path of the vibrator (11,13). While vibration of the reinforcing steel has been found to aid in the bonding of the concrete to the steel, the net result can be reversed if the vibration of the steel is performed excessively (7,20).

A paving vibrator should optimally have a head diameter of 2 to 3-1/2 in., a 0.2 to 0.7 in.-lb. eccentric moment, and a variable frequency (2,4,15). It should be noted, however, that the physical properties of the concrete have more influence on consolidation than the properties of the vibrator (16). A paving machine should be operated between 10 to 20 fpm, and optimally maintained between 12 to 14 fpm (12,13,16). Vibrators should be mounted horizontally above the reinforcement and as close to mid-depth as feasible (2,11,13). No research could be found concerning the influence of the position of the vibrators within the horizontal plane or with respect to the direction of travel of the paving machine.

It has been determined that the presence of chemical or mineral admixtures will affect the rheological properties of a concrete mixture. With the advent of superplasticizers there is a lack of information concerning their implications in the CRCP industry. There is a need for an understanding of their benefits and limitations.

While there has been a tremendous growth of research concerning consolidation of concrete pavements in the past several years, there has been a lot of redundant research and contradictory findings. The major problems in solving the mysteries of consolidation have been in the methods and approach of research. Currently, much is known about each of the contributing parameters surrounding consolidation of CRCP; however, since these parameters are so interrelated, it becomes mandatory to study them simultaneously in the most practical situations attainable within laboratory conditions.

Review of the Test Parameters

A review of available literature concerning each of the test parameters included in the laboratory investigation revealed some very valuable information necessary in developing and analyzing the laboratory study. For clarity and convenience, each of the test parameters has been discussed separately.

Consolidation vs. Depth in Pavement: It has long been the concern of those interested in the consolidation of CRCP that the concrete in the bottom of the CRCP slabs was not receiving adequate consolidation when compared to the concrete in the top of the slab. This concern is based on the fact that a CRCP slab contains a heavy mat of reinforcing steel at mid-depth which only allows the paving vibrators to be submerged to a position above this plane. For this reason, the vibrators are located in the top half of the CRCP slabs. Many researchers also believe that the reinforcement tends to dampen the effect of the vibrations as they are transmitted to the bottom portion of the slab.

The SDHPT appears to be interested in knowing if the concrete below the reinforcing steel is being adequately consolidated. Some research in the area tends to reinforce this concern. A study released by the United States Department of Transportation's Federal Highway Administration in March of

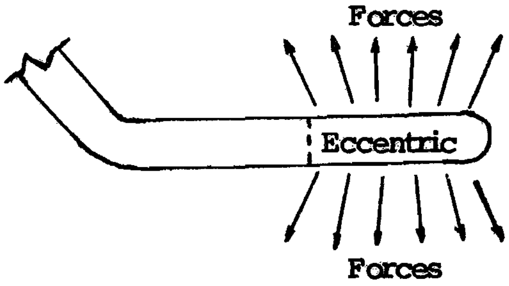
1977 stated that the top of the CRCP pavements was consolidated better than the bottom (18). However, also included in the 1977 study was that the use of a mesh depressor was found to contribute to the consolidation process. Since the mesh depressor pushes the steel down through the top of the CRCP slab to mid-depth, this influence would be more prevalently detected in the top portion of the concrete slab. The degree of the mesh depressor's contribution was not presented, therefore, the conclusion that the top of the slab was consolidated better than the bottom due to better vibration could be subject to question.

While concerns for the effectiveness of consolidation in the bottom of CRCP slabs are valid, there are also reasons to believe that, in fact, the concrete in the lower portion of the slab is subject to better consolidation than that in the top. It is generally accepted that concrete in the lower portion of a structure, such as that of a column, results in higher strength than the concrete above it. This is due to the loading produced by the overburden which aids in the consolidation of the concrete under it. The upper concrete's weight helps to force the solid material down and either move the air up or compress it into smaller voids. This same effect can be applied to what happens during the consolidation of a concrete pavement.

Another factor to consider, during the consolidation of CRCP, is that the vibrators move horizontally through the concrete. As they pass over an area, all of the solid material begins to seek a lower position, and the air tends to move upward. As the air moves up to the surface, the vibrators move out of the area and the internal friction of the mix is restored. When the mix becomes solid again, some of the air that was moving up through the slab is trapped in the upper portion of the slab. It would only stand to reason that, if the bottom was subject to adequate vibration while the vibrators were present, then it would have a lower void content than the concrete above it.

A look at the information contained in Figure 1 presents yet another interesting phenomenon.

Figure 1. Force pattern surrounding a paving vibrator.



As can be seen from this Figure, a paving vibrator produces forces at right angles to its head. Understanding that the vibrator is submerged in the top section of the CRCP leads to the conclusion that the forces acting on the concrete above the vibrator are acting upward. This will tend to force the concrete above the vibrator upward and counteract the forces of gravity that normally aid the consolidation process. Once again, it can be concluded that this effect would inhibit consolidation and tend to produce a greater concentration of voids in the concrete above the vibrator.

Also of importance is the fact that the vibrators are dragged through the upper portion of the concrete. They create a void channel in the upper portion of the concrete that has to be removed. While this problem is probably very slight and is extremely dependent on the paving speed, it could help in determining why the void content varies with the depth of the CRCP slab.

There is also documented information contained in a study released by the Texas Highway Department in 1969 that shows that the bottom of a CRCP had lower bulk densities and higher splitting tensile strengths than the top (7). While this was not a conclusion of the report, the information presented in the study documents this finding.

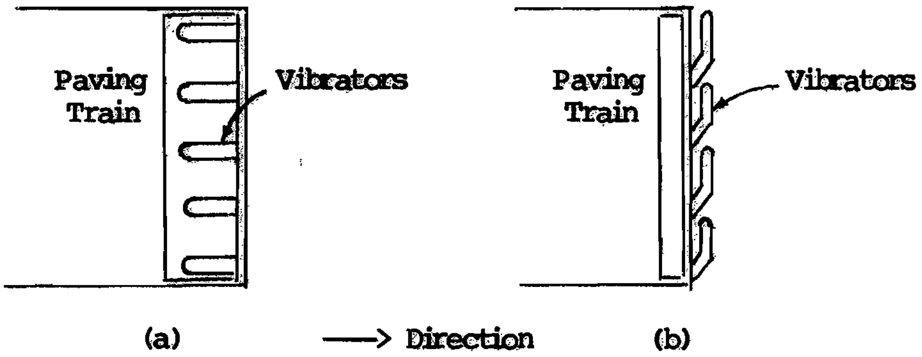
Consolidation vs. Vibrator Spacing: Numerous research studies have determined that vibrator spacing on gang-mounted paving machines has a pronounced effect on the degree of consolidation attained in CRCP (2,4,11,13, 20). The radius of action of a vibrator is defined as the distance away from a vibrator that the concrete can be adequately consolidated during the time period the vibrator remains in a particular position.

When investigating the spacing requirements of paving machine vibrators it is not enough to simply study the radius of action of a single vibrator submerged in fresh concrete. This method of study makes it impossible to determine the overlapping effect of the vibratory patterns experienced when two vibrators are mounted at various spacings. For this reason, a practical laboratory investigation designed to depict actual field conditions must incorporate the same vibratory patterns emitted by gang-mounted paving vibrators; thus, two or more vibrators must be studied simultaneously at various spacings. Another factor of importance is to insure that the vibrators used be of the same design and produce practically identical vibrations in the fresh concrete. This will aid in the coordination of the vibratory patterns as they overlap in the center of the space between the two vibrators.

Research has shown that consolidation and strength decreases with an increase in the distance away from a single vibrator (2,11,13). For this reason, it can be assumed that the worst possible condition for consolidation effort will be located at the centerline between the spacing of two vibrators. Therefore, when studying the effects of various spacing requirements, data should be gathered at the center of the space between the vibrators, and an analysis made to determine if the reduction of void content is great enough to require a smaller spacing.

Consolidation vs. Method of Mounting Paving Vibrators: The SDHPT currently specifies a vibrator spacing of no more than 24 in. on CRCP slip-form paving machines. It should be noted that the 24 in. maximum spacing requirement is intended to be applied to the spacing of paving vibrators when mounted so that they are parallel to the direction of travel, see Figure 2a.

Figure 2. Methods of mounting paving vibrators.



Presently, many CRCP paving contractors mount their vibrators perpendicular to the direction of travel (see Figure 2b) rather than the conventional way already mentioned (see Figure 2a). For this reason, it is clear that some research is necessary in order to determine the effect of this mounting procedure, and if the SDHPT's specifications should include a separate entry for the two methods of mounting.

There are several factors that should be considered when studying the effects of mounting the vibrators perpendicular to the direction of travel. Figure 1 (p. 10) reveals that the forces generated by a paving vibrator act at right angles to the head. This is of importance in that no vibrational forces are produced beyond the head of the paving vibrator. Also depicted in this Figure is the effect of where the eccentric weight is located within the head of the vibrator. It is this eccentric weight that produces the forces of vibration. Since the eccentric is located in the front half of the vibrator, the majority of the forces it produces are emitted from this part of the vibrator. The back half of the vibrator's head does transmit some of the vibrational forces, but they are of a smaller magnitude than those emitted from the front half of the vibrator's head. Therefore, paving vibrators mounted perpendicular to the direction of travel should be mounted at a maximum spacing equal to the length of their head. Ideally, vibrators mounted in this fashion should be mounted so that they overlap half of the length of the vibrator's head.

Another factor due consideration involves the effect of the speed of the paving train when vibrators are mounted perpendicular rather than parallel to the direction of travel (see Figure 3).

Figure 3. Force patterns for different vibrator mounting methods.

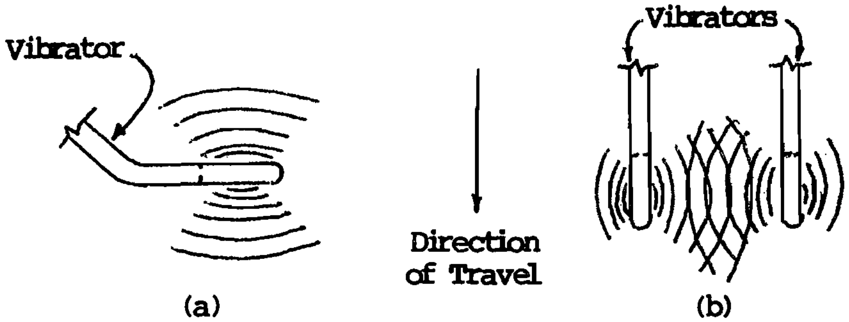


Figure 3b shows that the speed of the paving train is a function of the length of the effective part of the vibrator (the eccentric). Research has shown that for this method of mounting the optimum paving speed is between 12 to 14 fpm (<u>12</u>,<u>13</u>,<u>16</u>). By turning the vibrators perpendicular to the direction of travel, the paving speed is a function of twice the effective radius of action (diameter of action) of a single vibrator submerged in fresh concrete (see Figure 3a). Since this diameter of action is probably different than the length of the effective part of the vibrator (the eccentric), it could be expected that the paving speed would need to be reduced when the vibrators are turned perpendicular to the direction of travel in order to achieve the same level of consolidation. If the paving train speed was kept the same, it would be assumed that the concrete consolidated by the vibrators mounted perpendicular would be of lower quality than that vibrated by the conventional method. The diameter of action of a single vibrator moved through fresh concrete must be determined in order to recommend a speed for a paving train with vibrators mounted perpendicular.

Another difference in the effect of the two mounting methods can also be suggested. When the vibrators are mounted parallel to the direction of travel the concrete will receive varying degrees of vibration across the width of the pavement, depending on where it is between two vibrators. The concrete directly under a vibrator will receive the greatest amount of vibrational force, and this amount will decrease with an increase in the distance away from the vibrator. It would then be expected that the concrete would be consolidated in varying degrees across the width of the pavement.

When the vibrators are turned perpendicular to the direction of travel, this effect is not seen. If the vibrators are sufficiently overlapped and the paving speed properly set, then all of the concrete across the pavement receives the maximum vibrational forces that can be emitted. In effect, this mounting procedure attempts to produce an eccentric weight the width of the pavement that is broken into small sections, each producing a vibrational force on the concrete. What remains to be determined is how the concrete behaves when the vibrators move through it perpendicular to the direction of travel. Many questions will have to be answered to entirely understand these two very different methods of attempting to achieve the same result.

Consolidation vs. Coarse Aggregate Factor: The coarse aggregate factor is one way of describing the composition of a concrete mix. It is defined as the ratio of the bulk volume of coarse aggregate to the total volume of concrete, and it depends on the maximum size of the aggregate and on the grading of the fine aggregate (9). The shape of the coarse aggregate particles does not directly enter the relation since, for instance, a crushed aggregate has a greater bulk volume for the same weight (ie. lower bulk density) than a well-rounded aggregate. Thus, the shape factor is automatically taken into account in the determination of the bulk density (9).

When designing a concrete mix, the optimum ratio of the bulk volume of coarse aggregate to the total volume of concrete (coarse aggregate factor) is chosen based on the maximum size of the aggregate and the grading of the fine aggregate (fineness modulus). However, when the degree of consolidation, or the desired void content of the hardened concrete, is critical to the mix designer, then this property must also be considered. It is understood that the volume of coarse aggregate contained in a given concrete volume will influence the subsequent void content of that mix. This can be described by examining the properties of a fine and coarse grained mixture (see Figure 4) (21).

Figure 4. Various fine and coarse grained mixtures (21).

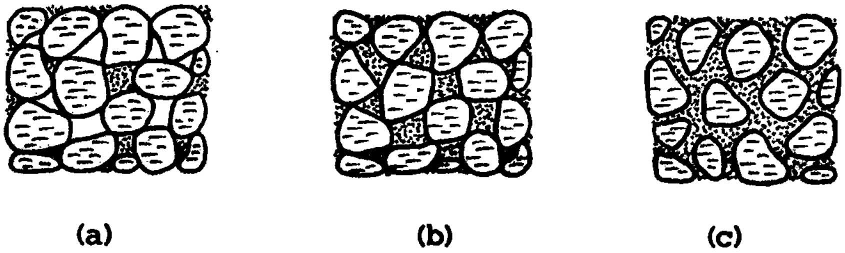


Figure 4 (p. 15) represents three possible combinations of a fine and coarse grained mixture. A mixture that contains little or no fines (Fig. 4a, p. 15) has stability due to the grain-to-grain contact of the coarse materials (21). However, this mixture inherently contains voids between the coarse grains due to a lack of fines necessary to fill all of the voids between contact points. A concrete mixture that has too high a coarse aggregate factor, or too high a volume of coarse aggregate, will tend to have a low density and a high void content irrespective of the degree of consolidation.

A mixture that has adequate fines to fill all of the voids between the coarse grains will still gain its strength from grain-to-grain contact, but with increased shear resistance (Fig. 4b, p. 15) (21). A concrete mix with the optimum coarse aggregate factor will have a high density, a low permeability and increased shear strength. The degree of consolidation will become increasingly important in this mix to assure that the fines are allowed to flow into all of the voids between the coarse grains. Once the concrete has undergone the initial slumping, during the consolidation process, it will be important to continue vibration until the entrapped air present in the mortar has been allowed to escape. This condition should lead to the optimum consolidation attainable for a given set of concrete materials.

A mixture that contains a large amount of fines, or too low a coarse aggregate factor, has no grain-to-grain contact, and the coarse aggregate merely "floats" in the mixture (Fig. 4c, p. 15) (21). A concrete mixture under these conditions will have a low density and a higher void content due to the entrapped air contained in the fines. Consolidation of this mix would have to be continued excessively in order to allow the entrapped air to rise to the surface. Since the coarse aggregate is free to float in the mix, and since the mortar is what carries the vibration after the initial slumping, this would tend to cause settlement of the coarse aggregate and an accumulation of fines on the surface.

From this discussion, it is obvious that there is an optimum coarse aggregate factor for a given set of concrete materials in order to achieve the highest degree of consolidation. Therefore, the degree of consolidation desired should also be considered, in addition to the maximum aggregate size and the fineness modulus, when choosing a coarse aggregate factor in the mix design procedure.

There presently exists one possible method for predicting the optimum coarse aggregate factor based on the materials to be used. The Fineness Modulus Method of mix design is centered on the concept that aggregate proportions and gradations can be used to design a concrete batch. The grading of aggregates is the distribution of particles among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of seive opening sizes or the percentage of material collected between two seive opening sizes. Standard seive sizes and testing procedures are specified for determining the gradation of fine and coarse aggregates. The grading and maximum size of aggregates used in concrete mixes affect relative aggregate proportions (coarse aggregate factor and fine aggregate factor) as well as cement and water requirements, workability, economy, porosity, shrinkage, and durability of the concrete. In general, aggregates that do not have a large deficiency or excess of any size and give a smooth grading curve will produce the most satisfactory results.

The fineness modulus of either fine or coarse aggregate is obtained by adding the cumulative percentages (by weight) retained on each of a specified series of seives and dividing the sum by 100. It is an index of the fineness of an aggregate- the higher the fineness modulus, the coarser the aggregate. Different aggregate gradings may have the same fineness modulus. Fineness modulus is useful in estimating proportions of fine and coarse aggregates in concrete mixtures. By knowing the fineness modulus of a given set of aggregates, the optimum coarse and fine aggregate factors can be determined and this should yield the best strength and porosity results.

Consolidation vs. Coarse Aggregate Size: The choice of the maximum size of the coarse aggregate is usually made prior to any considerations of the mix design. In reinforced concrete the maximum size of the aggregate which can be used is governed by the width of the section and the spacing of the reinforcement. It has also been accepted that the maximum size of the coarse aggregate will influence the void content of the hardened concrete; therefore, the desired void content of the concrete must also be considered when choosing the maximum coarse aggregate size.

It has generally been considered desirable to use as large a maximum size of aggregate as possible. However, it now seems that the improvement in the properties of concrete with an increase in the size of the aggregate does not extend beyond 1-1/2 in. so that the use of larger sizes may not be advantageous (9). This can be verified by an examination of what occurs as the maximum aggregate size is increased to 1-1/2 in. and then beyond. The larger the aggregate particle the smaller the surface area to be wetted per unit weight (9). Thus, extending the grading of aggregate to a larger maximum size lowers the water requirement of the mix, so that, for a specified workability and richness, the water/cement ratio can be lowered with a consequent increase in strength (9). This behavior has been verified by tests with aggregates up to 1-1/2 in. maximum size. Experimental results show that above the 1-1/2 in. maximum size the gain in strength due to the reduced water requirement is offset by the detrimental effects of lower bond area (so that volume changes in the paste cause larger stresses at interface) and of discontinuities introduced by the very large particles, particularly in rich mixes (9).

Therefore, as the maximum aggregate size increases to 1-1/2 in., it appears to add to the strength of the concrete. The problem now becomes one of determining the effect of this phenomenon on achieved consolidation. It has been determined in experiments funded by the SDHPT that a reduction of the maximum size of the aggregate from 2-1/2 to 1-1/2 in. will enhance consolidation of the concrete (7). Currently, the SDHPT specifies a maximum size of 1-1/2 in. coarse aggregate. It should now be determined if this specification should be modified further.

Consolidation vs. Superplasticizers: Superplasticizers are a relatively new family of admixtures which can either be used as high-range water reducers or be incorporated to produce "flowing" concrete. They were introduced into North America in 1976 and since then a number of research laboratories have been developing data on their effect on hardened concrete (22).

There are three possible ways in which superplasticizers may be used in concrete (22):

1. To produce concrete with a very low water/cement ratio (22). This will develop high strength concrete since the water content is reduced while the cement content remains the same. The loss in workability due to the decrease in the water content is compensated for by the superplasticizing agent.

2. To produce concrete with reduced cement content (22). The same strengths can be obtained by lowering both the cement and water contents so that the water/cement ratio is maintained. Again, the loss in workability is compensated for by the superplasticizing agent.

3. To produce flowing concrete (22). Superplasticizers may be added, with

no change in the mix proportions, simply to increase the slump and produce a more flowable mixture.

Since, in slip-form paving construction, the slump of the concrete mixture must be maintained, the only other advantage in using superplasticizers would be to either conserve cement and produce equally strong concrete (as in method 2) or lower the water content and produce stronger concrete (as in method 1).

While research has shown that superplasticizers cause no increase in segregation or bleeding, no significant influence on the setting time of the fresh concrete, and no alteration of the freeze/thaw durability of the hardened concrete, they do promote a high rate of slump loss (22). This rapid rate of slump loss in superplasticized concrete is a serious disadvantage and research is being conducted to find a solution to the problem. Presently, concrete containing a superplasticizer will provide a large increase in slump, but this increase is of short duration, and within 30 to 60 min. the concrete reverts back to the original consistency (22). This phenomenon is accentuated with elevated temperatures.

Currently, there are various methods available for counteracting the problems of rapid slump loss caused by the addition of superplasticizers. One solution involves the use of set retarding admixtures that can be combined with the superplasticizers. The purpose of these set retarders is to retard the rate of hardening of the concrete, therefore reducing the rate of slump loss.

Consolidation vs. Acceleration: Most references cited tend to agree that acceleration is the most significant parameter affecting concrete compaction by vibration (13,16,18). This, however, is not surprising; as can be noted by a close examination of what acceleration really denotes.

The vibrations produced during the consolidation process are most conveniently depicted by uniform harmonic oscillations. For simple harmonic motion the following fundamental relation exists between acceleration, frequency, and amplitude of vibration:

$$\text{Acceleration} = (2 \times \pi)^2 \times (\text{Frequency})^2 \times (\text{Amplitude})$$

Therefore, if it can be determined that a given concrete mix requires a certain level of acceleration to overcome the internal friction and consequently produce optimum consolidation, then a vibration can be produced by varying either the frequency, amplitude, or both, in order to obtain this level of acceleration. Since the frequency on some vibrators produced today can be adjusted, and since acceleration is most sensitive to the frequency (since the frequency is a squared value), it should be a simple matter to obtain a desired acceleration value. Amplitude of a given vibrator will always remain the same since the amplitude is a function of the eccentricity, the weight of the eccentric, and the weight of the vibrator itself.

This idea coincides with what has been the theory of many concrete researchers over the years. Many investigators believe that there is an optimum frequency and amplitude level for each different mix of concrete (23). They have not, however, been able to agree on a method for predicting these values.

The problem with this approach evolves in the fact that, while there has been some research into the study of acceleration, there has not been enough research in extremely stiff concrete mixes vibrated in mass quantities to determine the amount of acceleration necessary to produce optimum consolidation. Since most concrete used in the construction of CRCP is of similar mix characteristics, this level of acceleration needs to be investigated and determined. It needs to be determined if acceleration can be used as a tool to determine the frequency level needed of a group of vibrators to produce the best compaction effort. This method of approach will give researchers a scientific basis for study rather than the historical trial and error method of investigation.

Accelerometers have been used successfully in research to determine the patterns of acceleration present in concrete subject to vibration (16). More research using accelerometers in CRCP concrete during vibration would help to determine exactly what is happening and what can be done to improve the level of consolidation obtained. By taking various acceleration readings in different positions above and below the path of a vibrator as it moves through fresh concrete, a three-dimensional acceleration pattern could be constructed. The coordinates would include: time, distance, and acceleration. This could be the best method available to determine the radius of action of a given vibrator at a constant frequency level.

CHAPTER III

DEVELOPMENT AND PERFORMANCE OF THE LABORATORY INVESTIGATION

Purpose of the Laboratory Investigation

The purpose of the laboratory investigation was to determine the effect of the following variables on achieved consolidation:

a. Coarse Aggregate Factor

b. Coarse Aggregate Size

c. Vibrator Spacing

d. Superplasticizers with and without set retarders

e. Position of vibrators with respect to the direction of travel.

Also of importance during the laboratory study was an analysis of the variability of consolidation with the depth of the CRCP slab and the determination of whether CRCP consolidation could effectively be predicted and controlled by measuring the accelerations present during the consolidation process. The remainder of this Chapter describes the performance of the laboratory investigation.

Development of the Concrete Batch Designs

The first step in developing the concrete batch designs involved setting values for each of the variables outlined in the Purpose of the Laboratory Investigation. In an effort to determine if the maximum allowable coarse aggregate size presently specified for CRCP construction should once again be reduced, tests were designed to compare the effects of 1-1/2, 1, and 3/4 in.

coarse aggregates. To compare the effects of varying the coarse aggregate factor, tests were incorporated to include coarse aggregate factors of 0.85, 0.80, and 0.76. Tests were designed to analyze the effects of placing vibrators perpendicular to the direction of travel versus placing them parallel to the direction of travel, and to determine if superplasticizers (both with and without set retarders) would benefit the CRCP. Finally, tests were developed to determine the effect of spacing variations on consolidation. Currently, the SDHPT specifies a maximum spacing of 24 in.; therefore, spacings of 24, 18, and 12 in. were examined.

For the 5 variables listed in the Purpose there are 162 different combinations that could be studied. However, to maintain a reasonable program size, 11 of these possible test combinations were selected (Table 1, p. 25). To measure the degree of variability between batches, each of the 11 tests consisted of 4 replicate batches.

The second step of the concrete design involved the testing of the coarse and fine aggregates to determine their respective properties. The results of the tests on the coarse and the fine aggregate are contained in Appendix A.

The third step involved the development of the 6 basic mix designs (Table 1, p. 25) necessary for the implementation of the 11 tests previously described. Design values were selected from the Texas Highway Department's "Standard Specifications for Construction of Highways, Streets and Bridges" (Table 2, p. 26). A cement factor of 5.5 sk/cy, an air content of 5.0%, and air entrainment were used in each initial batch design. With this information, the test results contained in Appendix A, and the design process contained in the Texas Highway Department's "Construction Bulletin C-11", the initial mix designs were developed.

The final step in developing the concrete batch designs consisted of

Table 1. Test combinations and mix designs.

Coarse Aggregate Max. Size (in.)		1-1/2			1	3/4
Coarse Aggregate Factor		0.85	0.80	0.76	0.76	0.76
Method of Mount	12 in. Spacing		1 / 3			
	18 in. Spacing	2 / 6	1 / 1	3 / 5	4 / 7	5 / 8
	24 in. Spacing		1 / 2			
	Perpendicular to Travel Direction (without plasticizer)		1 / 4			
	18 in. Spacing (with plasticizer)		6 / 9			
	Perpendicular to Travel Direction (with plasticizer)		6 / 10			
	Perpendicular to Travel Direction (with plasticizer/retarder)		6 / 11			

Note: The numbers within the table signify the batch design numbers and the test numbers used in the laboratory investigation. A / B denotes that A is the batch number and B is the test number.

Table 2. Selected SDHPT specifications for CRCP.

Item	Specification
Cement Factor	Unless otherwise specified on the plans the concrete shall contain not less than 5 sacks of cement per cubic yard.
Air Content	Entrain 5% air +/- 1% based upon measurement made on concrete immediately after discharge from the mixer.
Coarse Aggregate Factor . . .	Shall not exceed 0.85
Water/Cement Ratio	Shall not exceed 6.25 gal/sk or 0.553 lb/lb.
Slump	Shall not be less than 1 in. or more than 3 in., designed to be 1-1/2 in.
Flexural Strength	Shall not be less than 575 psi at 7 days.

Note: These selected specifications were taken from Item 366 (1).

mixing 1.5 cu.ft. trial batches to determine whether or not the mix designs met the SDHPT's specifications for CRCP concrete (Table 2, p. 26). During the mixing process, attempts were made to produce concrete that had a 1-1/2 in. slump and an air content of 5.0%. Each time a trial batch was made, the amount of air entraining agent and superplasticizing admixture used were recorded along with the amount of water necessary for a 1-1/2 in. slump and the subsequent air content of the concrete. One beam (ASTM C192-81)[1] and two cylinders were cast for each batch, and they were cured for 28 days in a 95% relative humidity, 77°F, environmentally-controlled room. After 28 days the cylinders were tested for compressive strength and the beams tested for Modulus of Rupture. When a batch was prepared that had an acceptable slump and air content, it was considered a "successful" batch design. The 6 "successful" batch designs may be found in Appendix B. (Strength did not turn out to be a critical design factor, which was probably due to the use of a higher cement factor than the recommended minimum and a curing time of 28 days versus a 7 day curing time in the specifications.)

Development of the Testing Program

The next stage of the laboratory investigation involved the development of a testing program that could be performed within the laboratory under controlled conditions. Of vital importance in the development of this stage was the consideration given to see that the laboratory test closely simulated what would be expected to occur in the field.

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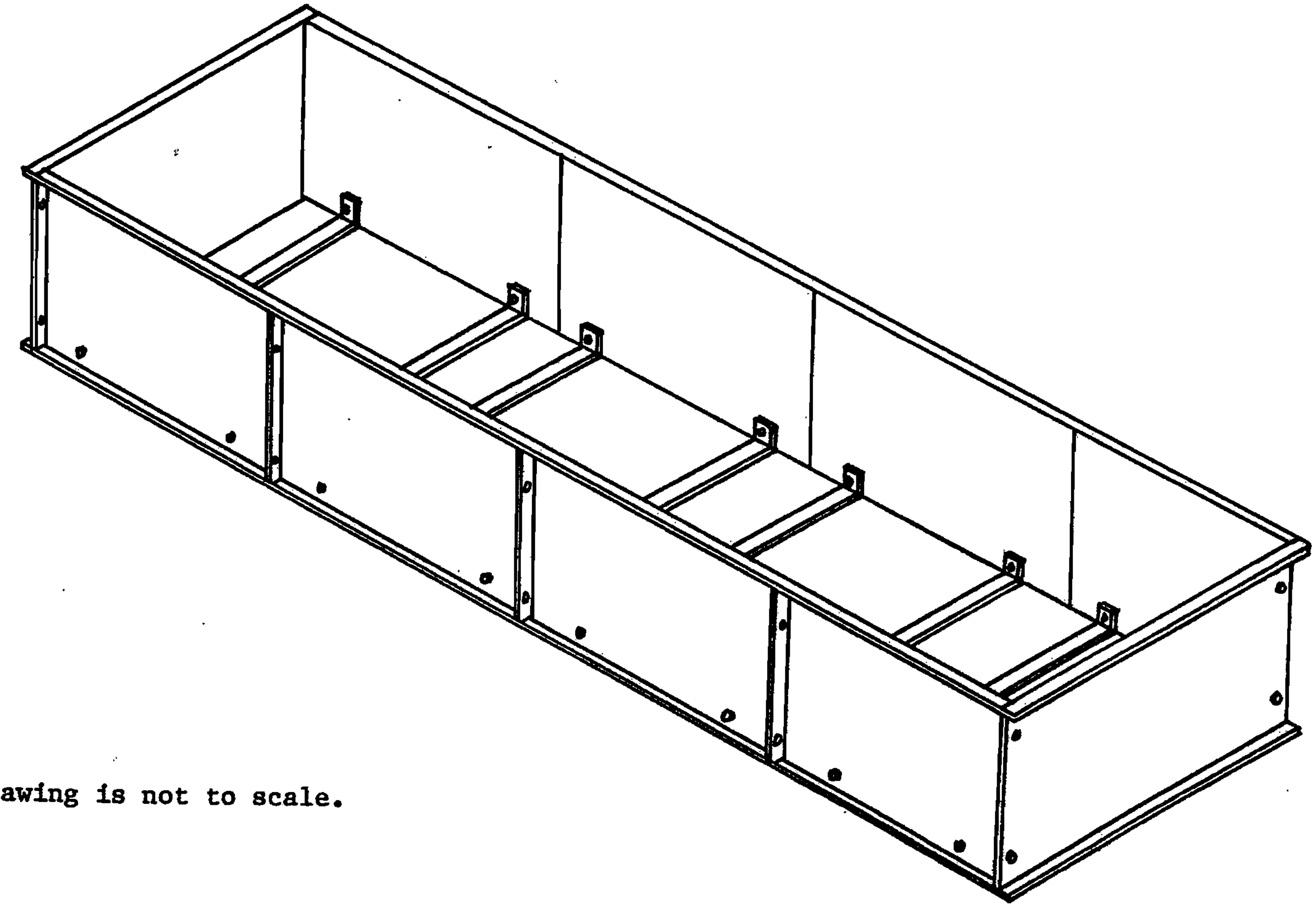
[1] All ASTM citations are included in reference (24).

It was decided that the laboratory test would consist of the batching of sidewalk-sized, simulated CRCP slabs. To cast the CRCP slabs, a set of metal forms was used that could be connected to produce 4 identical 27 in. x 24 in. x 10 in. slabs in one single casting (Figure 5, p. 29). In an effort to simulate the hot, dry climate experienced in parts of Texas, the slabs were to be cast in a 104°F environmentally controlled room. A 4 in. layer of compacted gypsum was constructed on the floor of the environmental room to simulate the damping effect of a base material. The metal forms were then placed on top of the base material. The forms were lined with a closed-cell foam pad to dampen any vibration that might have been transmitted through the metal forms. A steel mat of #4 and #6 bars was placed in each of the 4 slab forms at approximately mid-depth (Figure 6, p. 30).

Two Maginniss HPV-3 paving vibrators, which meet the performance requirements mentioned in Chapter 2, were mounted on an adjustable frame constructed to simulate mounting on a paving machine (Table 3, p. 31; Figure 7, p. 32). The frame allowed for the spacing of the vibrators to be varied, the height of the vibrators to be altered, and the vibrators to be mounted parallel or perpendicular to the direction of travel. A high-cycle generator was obtained to power the vibrators during operation.

Within the third slab of the forms, 4 accelerometers were used to measure the accelerations occurring in the fresh concrete during vibration (Figure 8, p. 33). The accelerometers were located in 4 critical locations: above and below an area of no reinforcement, and above and below an area where two reinforcing bars crossed (Figure 6, p. 30). A microcomputer was used to record acceleration values every 1/6 sec. during the entire consolidation process. The values were stored on a computer disc for later evaluation.

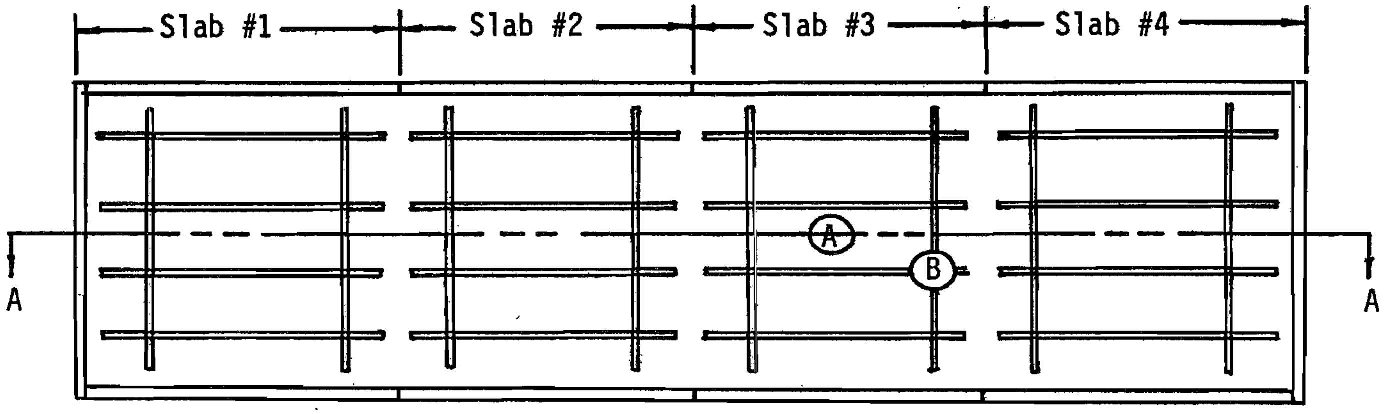
Figure 5. Forms for the simulated CRCP slabs.
(8'-0" x 2'-3" x 1'-0")



Note: This drawing is not to scale.

Figure 6. Entire simulated CRCP form design.

(a) Plan view.



Location A..... Accelerometer #1 above and #2 below.
Location B..... Accelerometer #3 above and #4 below.

(b) Section A-A

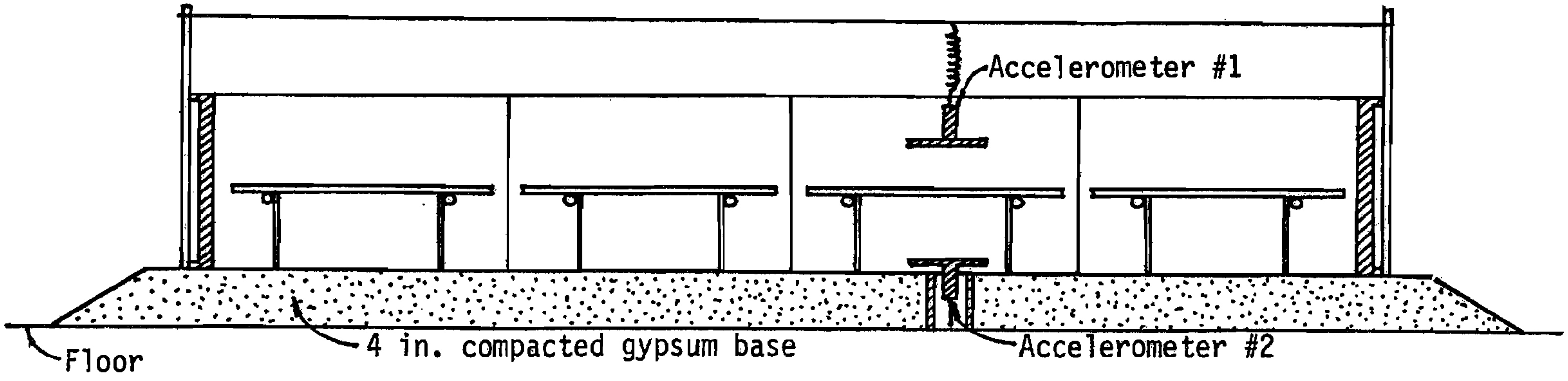


Table 3. Specifications of the Maginniss HPV-3 Hicycle Paving Vibrator.

Item	Specification
Head Diameter	2-3/8 in.
Head Length	18 in.
Total Weight	41 lb.
Eccentric Assembly Weight	5 lb.
Amplitude	0.0480 in.
Frequency	9600 - 11,000 vpm

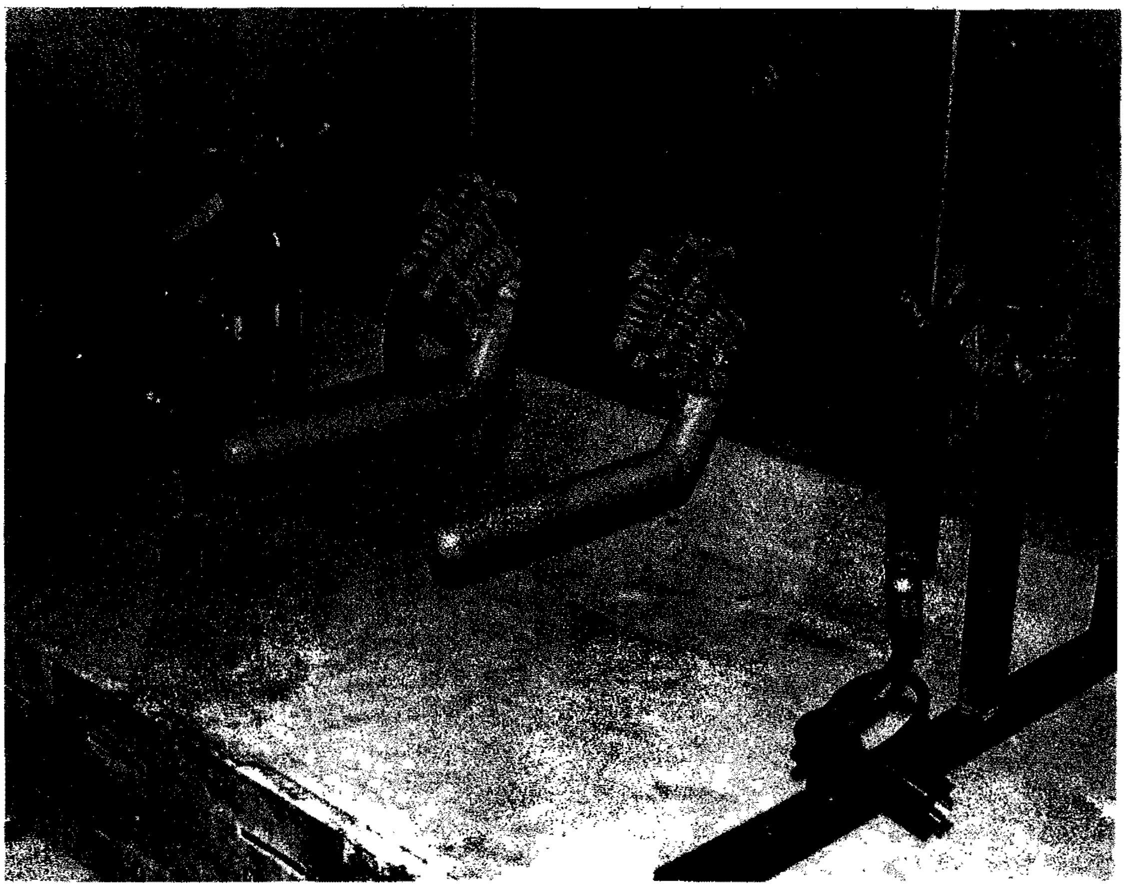
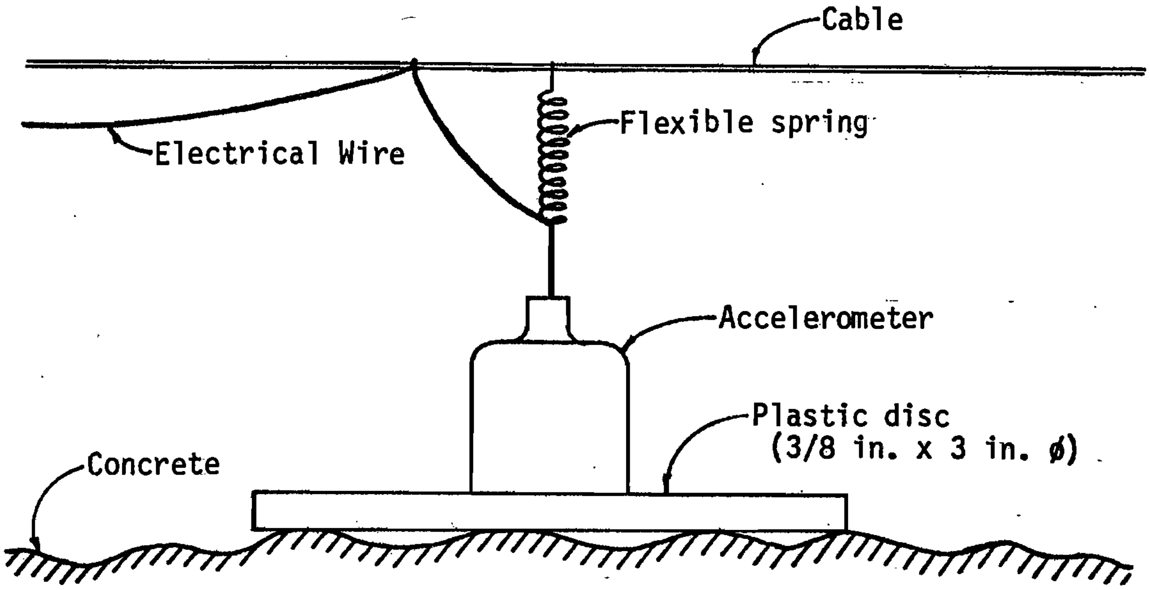
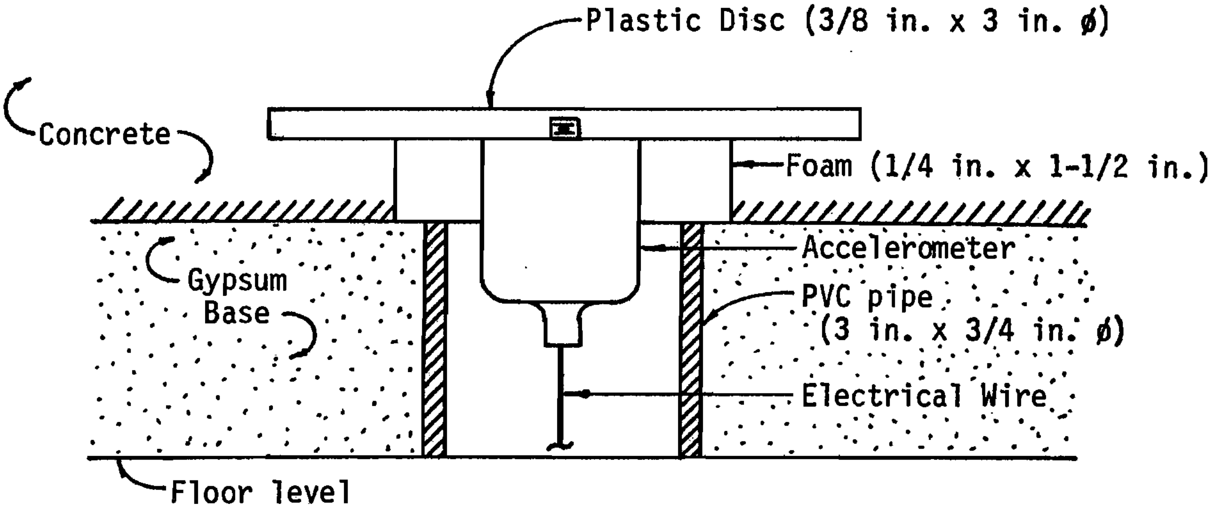


Figure 7. Mounting of the vibrators.

Figure 8. Mounting of the accelerometers.



(a) The top accelerometers.



(b) Section through the bottom accelerometers.

The Batching Process

When all of the equipment was prepared in the environmental room, the batching process began. The 4 batches in each test were 5-1/2 cu.ft. and were batched separately in a 6 cu.ft. mixer. A time frame of 30 to 45 min. was allowed for the entire mixing and placement of the 4 batches.

Slump was the controlling factor in the batching process, and water was added so that a 1-1/2 in. slump was achieved. One test cylinder was cast per batch, and a beam was cast from each of 2 randomly selected batches. Also, the air content, unit weight, and temperature was measured and recorded for each batch. The actual mix design values for each test can be found in Appendix C.

The concrete was quickly transported in wheel barrows from the mixer to the forms as each batch was completed. Once all of the concrete was in place, and all cylinders and beams prepared, the computer controlling the accelerometers was activated, and the vibrators were moved through the length of the forms at an approximate rate of 12 to 14 fpm.

After consolidation, the surface was hand troweled and steel sheet dividers were placed between each of the 4 slabs. Finally, the slabs were covered with a curing compound and allowed to cure at 104°F for 24 hours. At the end of this 24 hour period, each of the slabs were moved outside, covered, and allowed to cure until they reached an age of 28 days.

The cylinders and beams were covered and allowed to cure for 24 hours at room temperature. At the end of this 24 hour period they were moved to a 95% RH, 77°F, curing room where they were allowed to cure until they reached an age of 28 days.

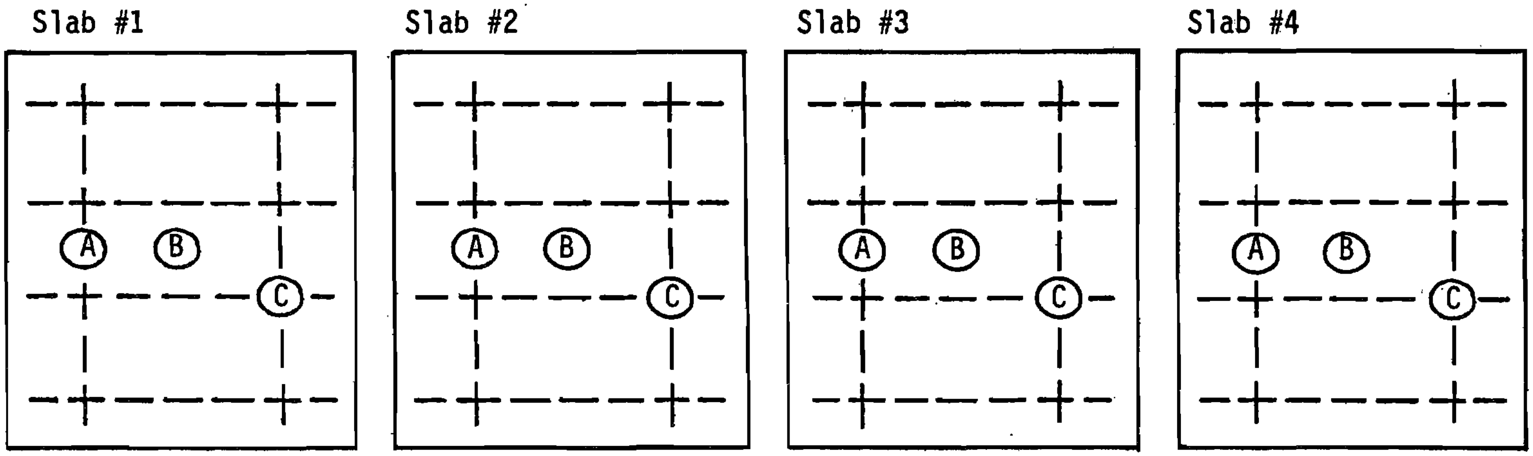
Concrete Testing

At the end of the 28 day curing period, the cylinders were tested for compressive strength, and the beams were tested for Modulus of Rupture. The results of these tests can be found in Appendix D.

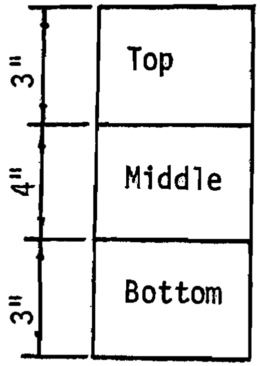
At this same time, the slabs were cored at locations shown in Figure 9 (p. 36). The cores were then sliced into 3 pieces: top, middle, and bottom. The Saturated-Surface Dry (SSD) unit weight, the dry unit weight, the void content, and the splitting tensile strength were determined for each of the top and bottom slices. The splitting tensile strength test was modified since our test specimens did not meet the requirements of the test. The SSD unit weight, the dry unit weight, and the void content were determined for the middle slices that contained no reinforcing steel. Finally, the void content was determined for the middle slices that did contain reinforcing steel. The results of these tests can be found in Appendix E.

Figure 9. Coring pattern and labeling technique.

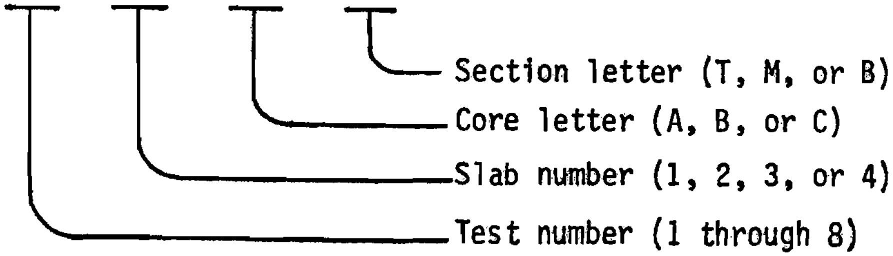
(a) Coring pattern.



(b) Core sectioning.



(c) Core labeling technique (Example: 1:3AT, denotes Test 1, Slab #3, Core location A, and the Top section.)



CHAPTER IV

DISCUSSION OF THE RESULTS

Introduction

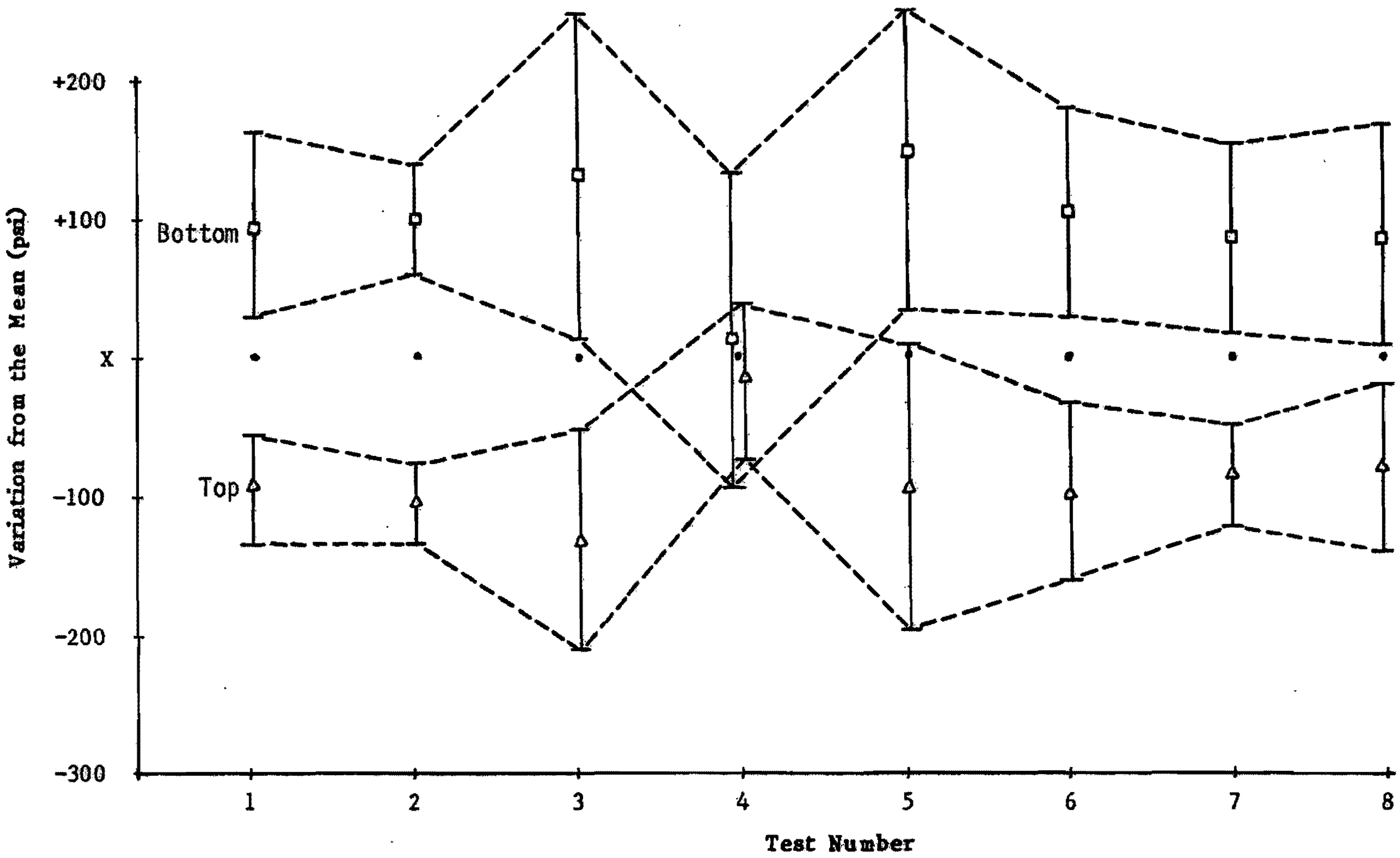
This Chapter presents the results of the extensive testing and analysis program conducted as part of the laboratory investigation. Conclusions are drawn in accordance with the effects of each of the parameters tested on the achieved consolidation of the CRCP slabs. The results are categorized according to the parameter being investigated.

Consolidation vs. Depth in Pavement

This study incorporated an analysis of the data to determine if the bottom of the simulated CRCP slabs was receiving less consolidation than the top. Examination of the void content, the splitting tensile strength, and the percentage of coarse aggregate fractured in the failed core sections was done to perform the analysis.

By examining the data gathered from the splitting tensile strength tests, it was quickly noted that the concrete in the lower portions of the slabs was stronger than that in the top. Figure 10 (p. 38) shows a plot of the splitting tensile strengths determined for the upper and lower portions of each core taken from batches 2 and 3 within 8 of the tests performed (the tests using superplasticizers were omitted from this section due to the erratic results obtained). The reason for using data from batches 2 and 3 only is explained in Appendix F. The plots for each test were normalized since the relative strength of one test to another was of no concern in this analysis. The mean values for the splitting tensile strength of all core sections broken within each test were

Figure 10. Normalized splitting tensile strength for each test.



Note: This figure has been normalized so that all of the overall mean values for each test fall at the same y-coordinate. About these normalized means are plotted the mean of the top and bottom of each test +/- one standard deviation (using selected data).

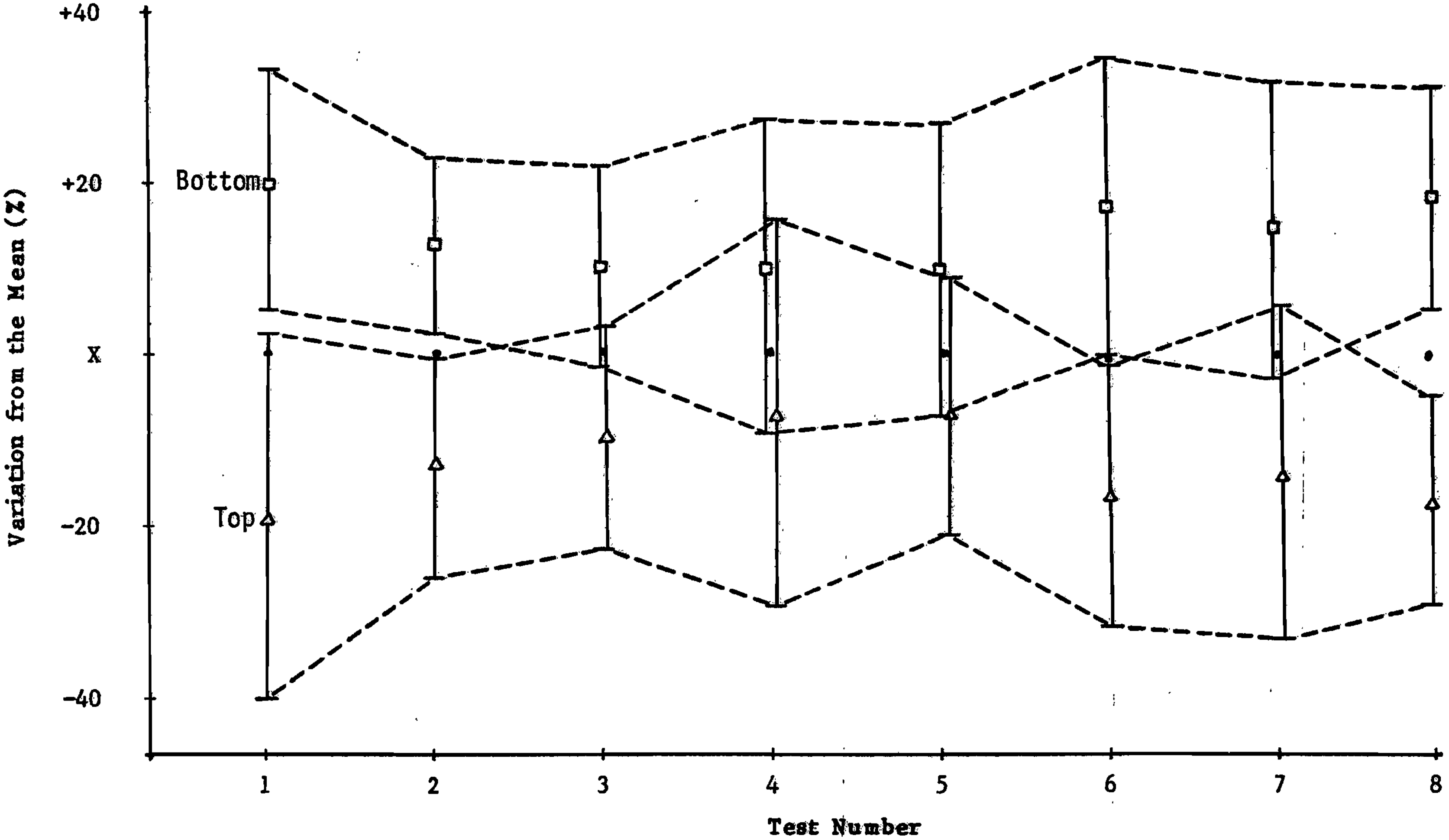
plotted on the same coordinate, X, along the vertical axis. About the mean, in each test, were plotted the average splitting tensile strength values for the upper and lower sections of the cores taken, along with their respective standard deviations.

Every test performed, where the vibrators moved parallel to the direction of travel, resulted in the lower portions of the concrete being indisputably stronger than the upper portions. None of these tests even had an overlapping of the standard deviations. This data alone would prove very conclusive in suggesting that consolidation was better in the lower portions of the CRCP. Even the test performed where the vibrators were moved perpendicular to the direction of travel showed that the splitting tensile strengths were better in the bottom of the slabs than in the top.

During the performance of the splitting tensile strength tests, data was gathered to record the percentage of coarse aggregate fractured in the failed samples. Figure 11 (p. 40) presents the results of these tests, where once again the mean values for the percentage of coarse aggregate fractured in all of the cores within each test were normalized to lie at the same coordinate, X, on the vertical axis. While this data is very subjective and was recorded solely at the discretion of the laboratory assistant, it is rather conclusive in its findings. Of the 8 tests conducted, only 4 had an overlapping of the standard deviation values, and none of these overlaps were significant enough to dispute the fact that the bottom of the simulated CRCP slabs had a higher percentage of broken aggregate in the failed core sections.

The existence of broken aggregate in the failed samples could suggest one of two things. An excess of fractured particles might suggest that the aggregate was too weak. However, if it is known that a good, strong aggregate was being utilized, then an excess of broken aggregate suggests that

Figure 11. Normalized coarse aggregate fracture for each test.



Note: This figure has been normalized so that all of the overall mean values for each test fall at the same y-coordinate. About these normalized means are plotted the mean of the top and bottom of each test +/- one standard deviation (using selected data).

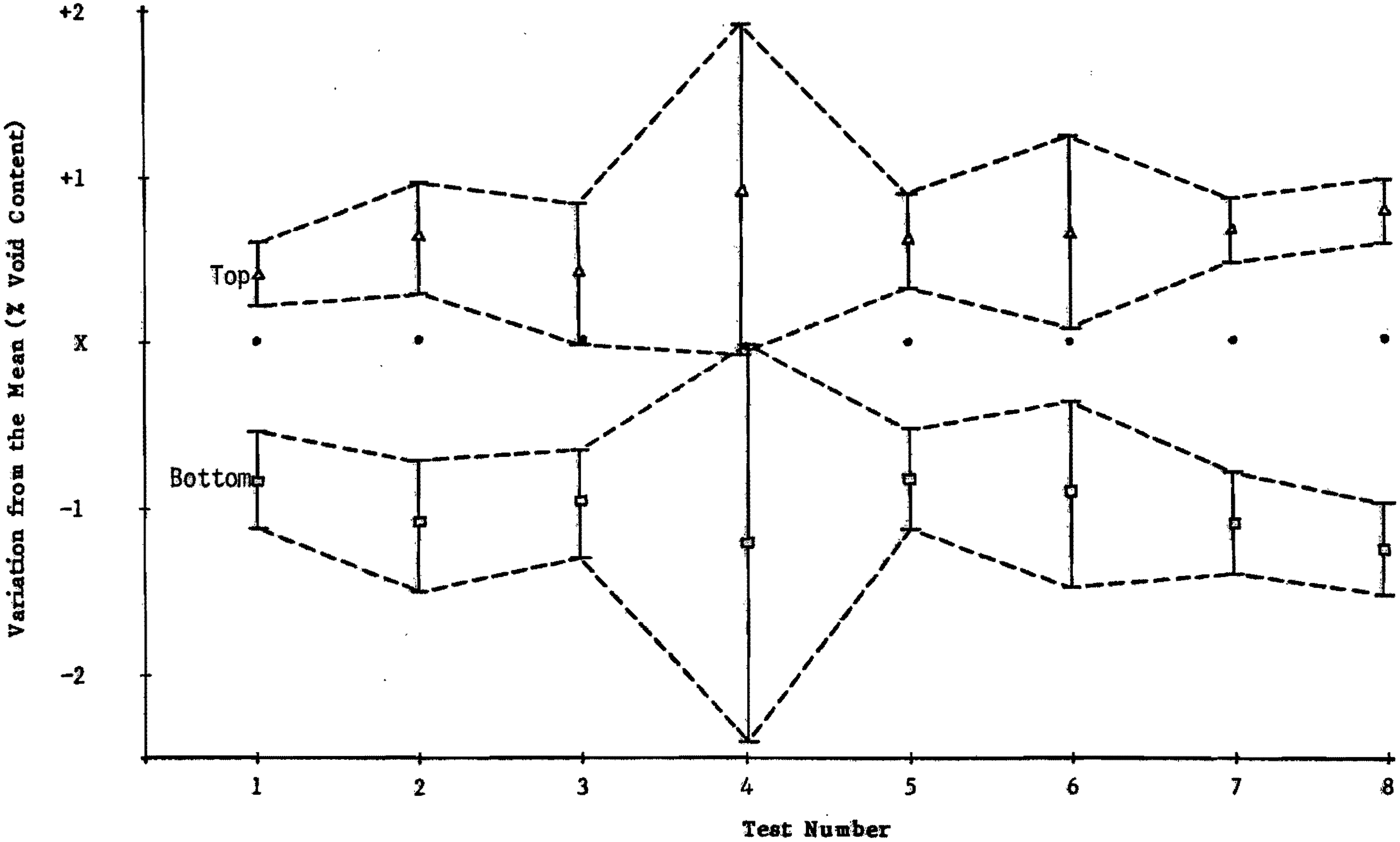
consolidation allowed the mortar to completely engulf the aggregate and caused it, being weaker than the mortar, to break first. The coarse aggregate used in this study was furnished by an aggregate supplier and was considered to be of adequate strength. The existence of adequate strength could also be suggested by the high specific gravity of the coarse aggregate (approx. 2.8). It could, therefore, be implied once again that the consolidation in the lower portions of the slab was more extensive than that in the upper portions.

Perhaps the most conclusive evidence of where consolidation was the best could be determined from an examination of the void content of the various tests. Figure 12 (p. 42) shows a plot of the void content determined for the upper and lower portions of each core taken from batches 2 and 3 within the 8 tests performed. Again, the plots for each test were normalized. As seen in the results of the splitting tensile strength tests, every test performed, where the vibrators moved parallel to the direction of travel, resulted in the lower portions of the concrete being indisputably more consolidated than the upper portions. The bottom of these slabs can be stated as being statistically more consolidated than the top since there is no overlap of the standard deviation values. The only test conducted where there was an overlap of the standard deviation values was that in which the vibrator was moved perpendicular to the direction of travel. Even in this test the overlap was so slight that the conclusion still holds.

Consolidation vs. Vibrator Spacing

This study incorporated three tests designed to compare the effects of consolidation efforts imparted at different vibrator spacings. Each test consisted of vibrators spaced at either 24, 18, or 12 in. It was the objective of

Figure 12. Normalized void content for each test.



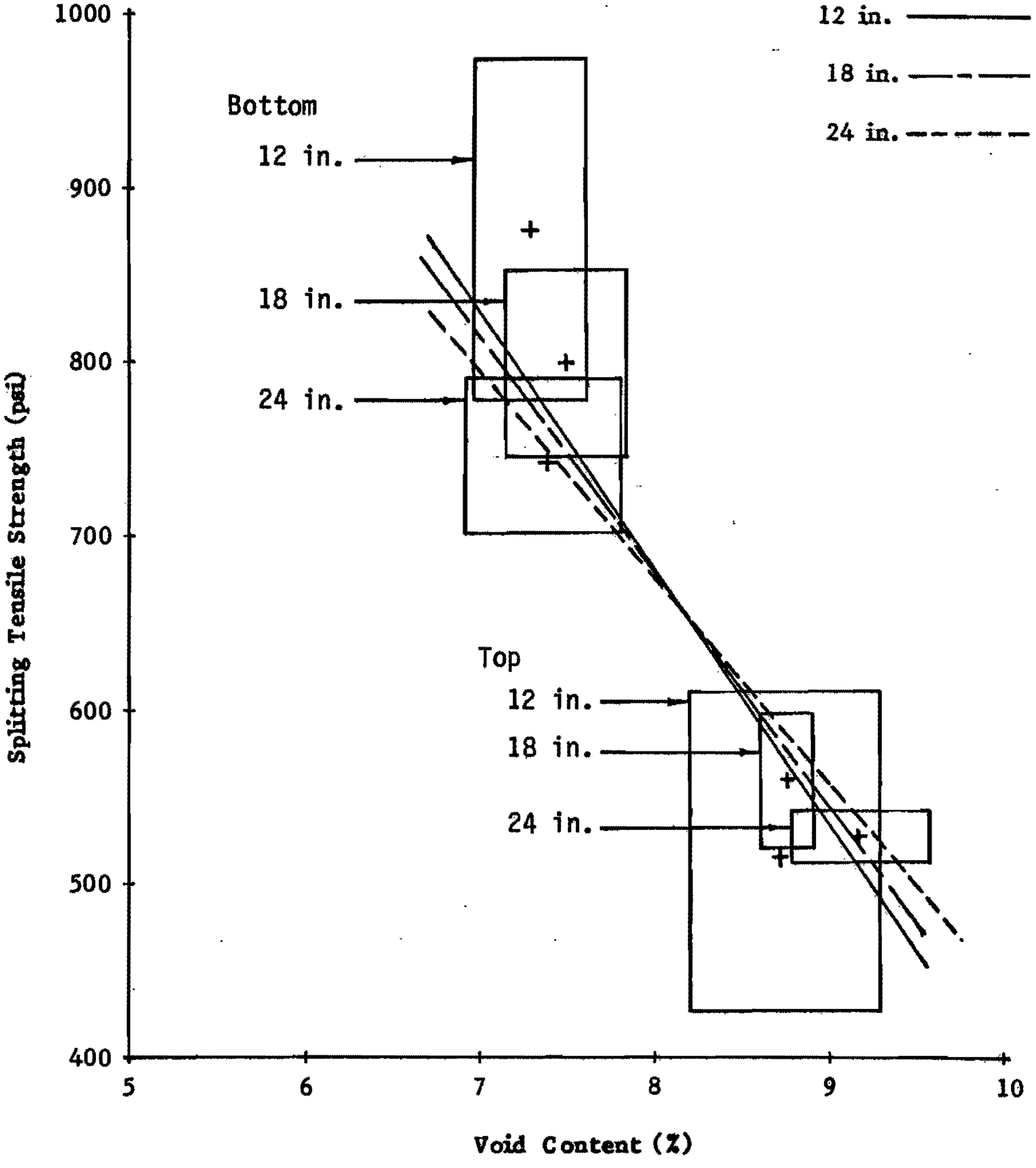
Note: This figure has been normalized so that all of the overall mean values for each test fall at the same y-coordinate. About these normalized means are plotted the mean of the top and bottom of each test +/- one standard deviation (using selected data).

this segment of the study to determine if a significant reduction of void content could be realized by reducing the maximum spacing requirement specified by the SDHPT.

The three tests were conducted with identical concrete mixes; the only variable employed in the tests was that of vibrator spacing. It would, therefore, be assumed that the relationship of void content to splitting tensile strength would be the same in all three cases. Analysis of these tests required only examining data taken from the centerline of the spacing between the two vibrators used. Probably the best method of comparing the tests with regard to their effects on consolidation was by displaying the relation of splitting tensile strength vs. void content. Splitting tensile strength was chosen to describe the strength of the concrete, and void content was chosen as a measure of the degree of consolidation achieved. Figure 13 (p. 44) presents the relation of splitting tensile strength vs. void content. Appendix F explains how this figure was developed, and Appendix G contains the data and statistics used in its creation.

Included in Figure 13 (p. 44) are linear regression lines prepared for each test to show the relation of splitting tensile strength vs. void content. Also included are the data and statistics from each test, depicted by the boxes on the Figure. These boxes are created by taking the mean values (depicted by the cross in the middle) and one standard deviation in each direction. Due to differences in consolidation found in the top and bottom sections of the simulated CRCP slabs, each test consists of two boxes; one to describe the concrete in the top and one to describe the concrete in the bottom sections of the cores. It was necessary to include the data information (the boxes) on the Figure since a change in test parameters could result in different degrees of consolidation for the same vibratory effort. This effect cannot be seen by

Figure 13. Effect of vibrator spacing on splitting tensile strength vs. void content.



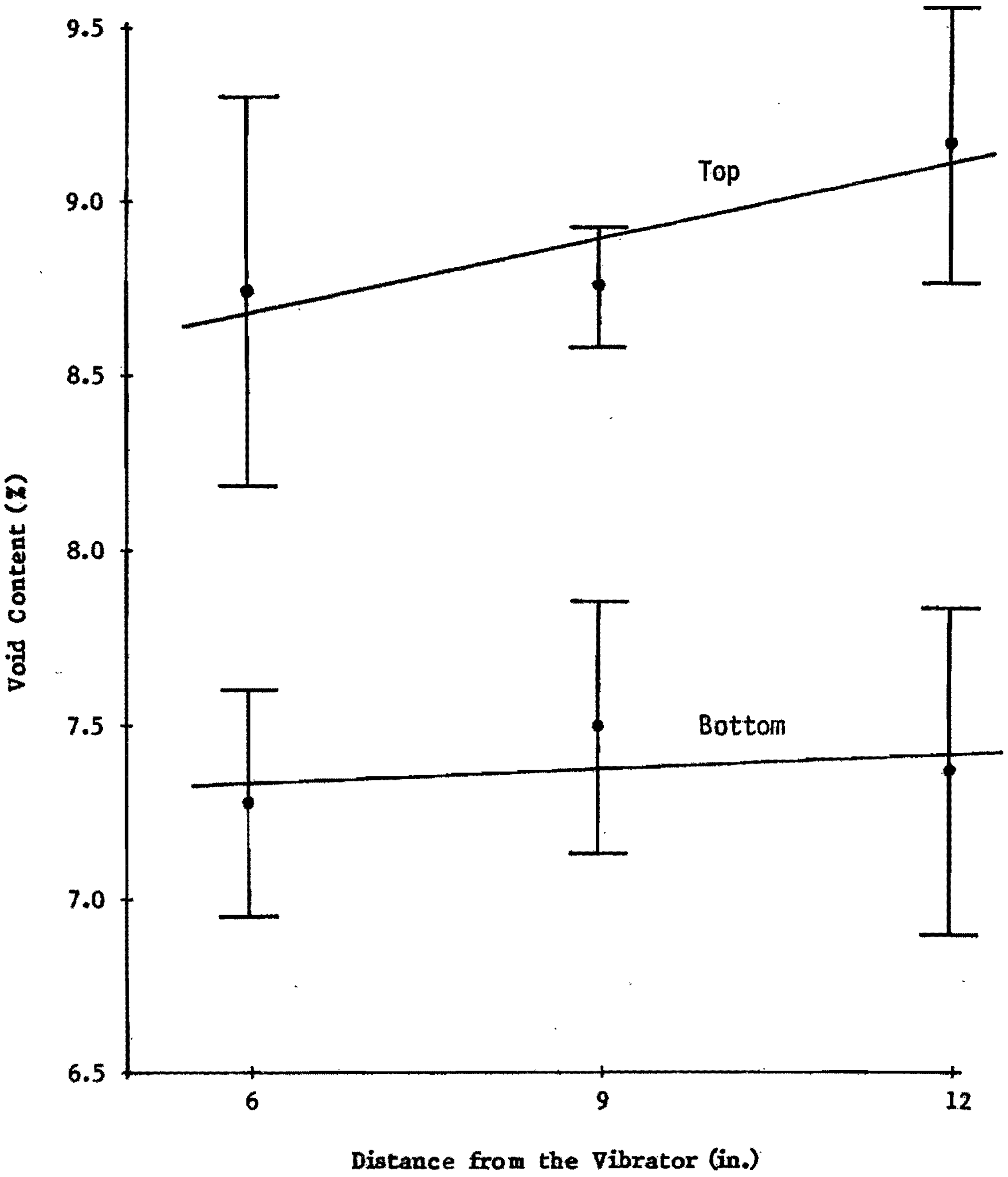
Note: Tests conducted with 0.80 coarse aggregate factor and 1-1/2 in. maximum size aggregate. The lines are linear regressions, and each box denotes mean values +/- one standard deviation.

merely examining the linear relationship of strength vs. void content. It has to be determined where along the linear relationship a given consolidation effort will produce results.

As expected, the linear regression lines seen in Figure 13 (p. 44) were almost identical for each of the three tests. Thus, the only property necessary to evaluate an optimum spacing requirement was that of void content. An analysis of the locations of the boxes in Figure 13 (p. 44) revealed that the void contents were very similar regardless of the vibrator spacing. With the statistical overlap it was hard to determine if, in fact, there was any difference in void content between the different spacings. For this reason, Figure 14 (p. 46) was included to determine the relation of varying the distance from the vibrator to the centerline of the space between the two vibrators.

Figure 14 (p. 46) depicts the relation of void contents observed as the distance from the vibrator was increased, and it consists of a plot of the mean void contents plus and minus one standard deviation. From this Figure it could be noted that the void content decreased as the distance from the vibrator was reduced, and this effect was more prominent in the top of the concrete cores than in the bottom. The consolidation in the bottom was virtually the same at all distances within this range. However, due to the increases in consolidation realized by a decrease in the distance from the vibrator in the top of the slabs, it could be concluded that the closer the vibrators are, the better the achieved consolidation would be. A look at the scale of the void content axis of Figure 14 (p. 46) revealed that even though the linear regression lines showed the smaller spacing to be better than the larger spacing, this difference was very minimal, on the order of only about 0.5% void content in the worst case. Therefore, care should be taken when making the judgement of whether one spacing is significantly better than another.

Figure 14. Effect of distance from the vibrator on void content.



Note: Tests conducted with 0.80 coarse aggregate factor and 1-1/2 in. maximum size aggregate. The lines are linear regressions (using all data) and the data plotted for each distance represents a mean value +/- one standard deviation (using selected data).

What could be determined from these data was that smaller spacings provided increased consolidation over larger spacings within the tested range. This finding coincided with what was assumed at the onset of the investigation. What remained to be determined was if a decrease in vibrator spacing from 24 in. would result in enough increase in consolidation to constitute lowering the maximum allowable spacing requirement.

The findings of this study did not present a reduction in void content large enough to constitute a reduction in the maximum allowable vibrator spacing. It should be noted that a decrease in spacing from 24 in. to 12 in. would necessitate the implementation of almost twice as many vibrators on the paving machine. Along with this increase in the number of vibrators would be an increase in cost attributable to the cost of the new vibrators, the additional maintenance costs, the additional equipment testing and monitoring costs, the additional operational costs, and the increased replacement expenses. Intuitively one would conclude that a 24 in. spacing is adequate for the consolidation of the CRCP. An analysis of the long term maintenance and replacement costs of the CRCP would be necessary to determine if a small reduction in void content is really worth the increase in construction costs necessary to provide it.

Consolidation vs. Method of Mounting Paving Vibrators

This study incorporated one test designed to simulate the effects of mounting a paving vibrator perpendicular to the direction of travel. Due to limitations on the size of the testing program, not all information necessary to make a comprehensive analysis could be obtained. The overlap of two vibrators mounted perpendicular to the direction of travel could not be simulated in the size of forms that were available. Therefore, a single vibrator was placed in the fresh concrete and moved perpendicular to the direction of travel at an approximate rate of 12 to 14 fpm.

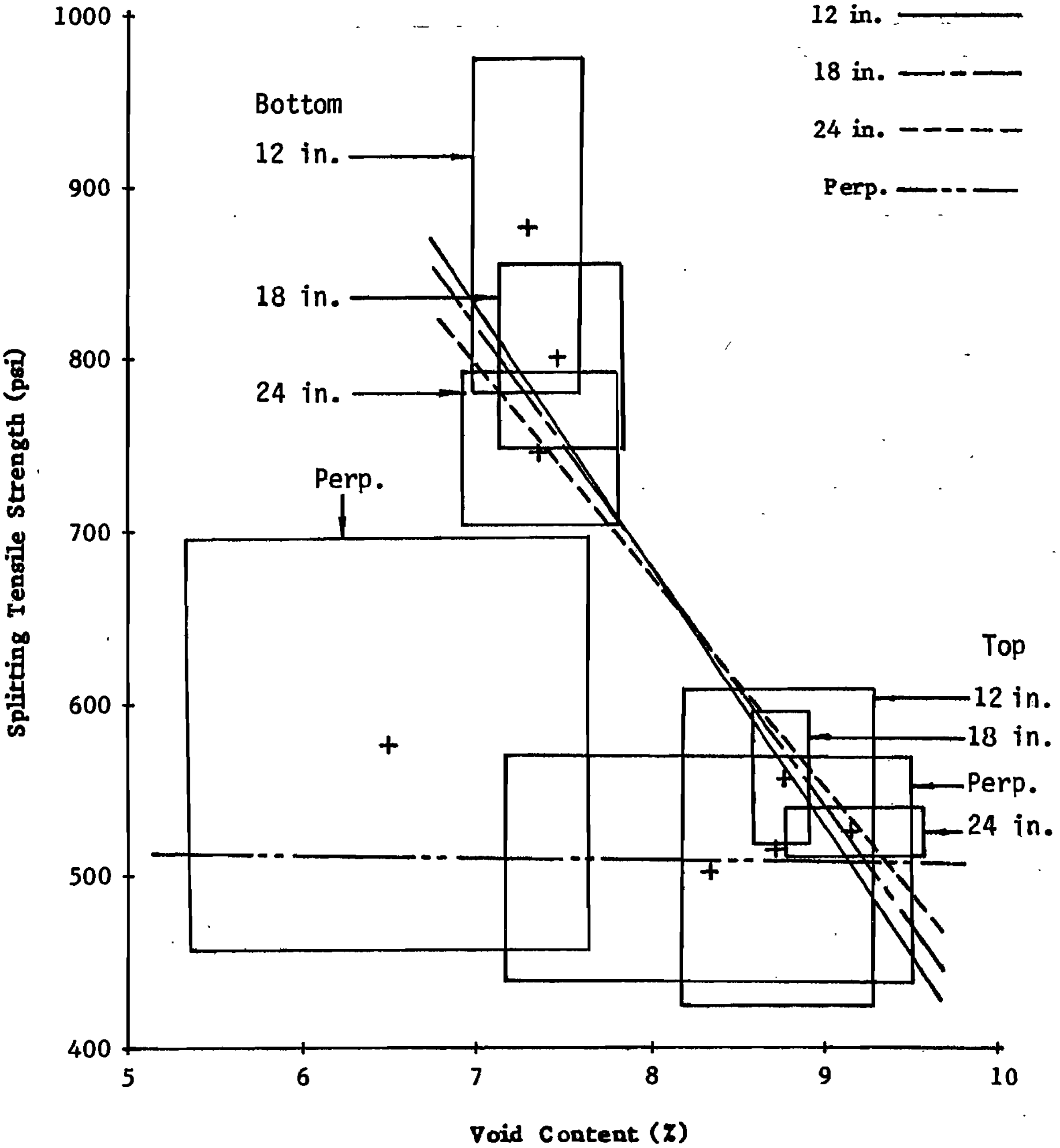
The results of this test could be compared to the results obtained from the three tests performed to analyze the effects of variations in the vibrator's spacing requirements. The concrete used in these four tests was of the same mix design making it possible to determine which method of mounting the paving vibrators was superior under the testing conditions.

First, a comparison of the quality of concrete obtained in the four tests was necessary. For this comparison, the results of the test performed with the vibrators placed perpendicular to the direction of travel were superimposed on the Figure displaying the results determined by varying the vibrator spacings (see Figure 15, p. 49). As determined in the section dealing with the effects of vibrator spacings, it would be assumed that the data gathered from the test where the vibrators traveled perpendicular would lie along the same linear regression lines as the data gathered from the other three tests. Figure 15 (p. 49) revealed that this was not the case.

Since it has been proven that there is a direct relationship between void content and splitting tensile strength for a given mix design, and since all of the concrete described by Figure 15 (p. 49) was of the same basic mix design, it could be concluded that there was a definite problem with the results displayed. In this case there was no coordination in the relationship between void content and splitting tensile strength for the two mounting methods. Due to the increased amount of data and more precise results obtained in the three tests where the vibrators were moved parallel to the direction of travel, this problem must be traced to the test where the vibrator was moved perpendicular.

In order to determine the nature of the problem, it was necessary to look at the entire test procedure to find if any unusual conditions were encountered.

Figure 15. Effect of different vibrator mounting methods on splitting tensile strength vs. void content.



Note: Tests conducted with 0.80 coarse aggregate factor and 1-1/2 in. maximum size aggregate. The lines are linear regressions, and each box denotes mean values +/- one standard deviation in each direction.

The actual mix design values (see Appendix C) revealed that, other than the test with the vibrator mounted perpendicular having a slightly lower amount of air in the mix and a slightly higher temperature, there were no significant differences in the fresh concrete properties. Therefore, the problem had to be somewhere else. A look at the strength test results from the cylinders and beams cast during the batching operations (see Appendix D) revealed that the test where the vibrator moved perpendicular had a slightly lower strength than did the other test's specimens. The reasons for this difference were not identifiable and could have been the result of insufficient compaction of the test specimens during casting procedures.

Probably, the most identifiable problem that could have been linked to the poor results of this test was observed while the concrete was being vibrated. It was noticed during the consolidation procedure that the concrete was not behaving as fluidly during vibration as it had during the tests where the vibrators were mounted parallel to the direction of travel. It appeared that the forces being transmitted outward from the vibrator in its direction of travel were not enough to liquefy the concrete before the vibrator passed over an area. Since, with this mounting procedure, the concrete was subject to maximum vibrations from the eccentric at only one instant as the vibrator passes overhead, the concrete received very little vibration once it lost its internal friction and became liquid.

A look at Figure 3b (p. 13) revealed that when the vibrators were moved parallel to the direction of travel the eccentric was above the concrete for the amount of time it took the entire length of it to pass overhead. However, Figure 3a (p. 13) showed that the concrete vibrated by a perpendicular vibrator was subject to maximum vibrations from the eccentric for only a short instant as it passed overhead. Therefore, the forces emitted from the vibrator when mounted perpendicular had to be great enough to overcome the internal friction of the mix and cause the initial slumping of the concrete so that the mortar could begin transmitting the vibrations and allow the air to rise to the surface.

The greatest task of a vibrator during the consolidation procedure occurred as it tried to overcome the internal friction of the mix in order to allow the air to begin moving upward. Since the forces emitted at the fringes of a vibrator's radius of action are so low compared to the forces near the head, it was very hard for the initial slumping of the mix to occur as the vibrator moved perpendicular to the direction of travel until the vibrator was almost directly above an area. This effect will be seen more clearly in the section dealing with acceleration. Also, since the concrete never really became liquid, the damping effect the mix put on the vibrator was tremendous and never allowed it to vibrate to its full potential.

With an understanding of how a problem with consolidation could have occurred when moving a vibrator perpendicular to the direction of travel, it had to be determined how this could effect the results of the tests on the core sections. The relationship between strength and void content has already been partially explained, but there are other factors that can enter into this relationship other than differences in the mix design. It is a known fact that the shape and distribution of the pores within the hardened concrete can have an effect on the resulting strength. It could have been that the voids in the concrete, although low by comparison to the other tests (see Figure 15, p. 49), were large enough and distributed in such a way that the splitting tensile strengths were greatly reduced.

Another factor for consideration might be the problems that could be encountered when performing the void content determination tests on the core sections. It could have been that actual SSD and submerged weights were not properly determined for the core sections due to their void distributions. The problems with this test are discussed in Appendix F, but are not thought to apply to this situation since a visual examination of the concrete slabs revealed that there was no significant concentration of voids along the inner walls of the holes where the cores were extracted.

Since the nature of the problem associated with the test performed where the vibrators moved perpendicular to the direction of travel could not be reliably determined, it was hard to draw any significant conclusions. It could be seen in Figure 15 (p. 49) that this concrete, while appearing to have a low void content, was of very poor quality in terms of strength. If, in fact, the test results were accurate, then the low splitting tensile strengths suggested that the voids were of such a size and distribution that they produced a very weak concrete. This would also suggest that problems might be encountered due to frost susceptibility and low durability. It would, therefore, be concluded (with some reservations) that mounting the vibrators perpendicular to the direction of travel is not beneficial to the effects of consolidation on concrete pavements if the same paving speed as used for parallel mounted vibrators is employed.

The problem of obtaining liquefaction of the concrete when mounting the vibrators perpendicular to the direction of travel was not verified in the field project on State Highway 288 in Houston. Although this type of mounting creates blind spots in the top of the concrete with very little vibrational effort transferred to the fresh concrete, the follow-up by a vibrating pan type vibrator immediately following the spud vibrators apparently provide adequate vibration in the concrete which slump value varied between 7/8 and 3 inch.

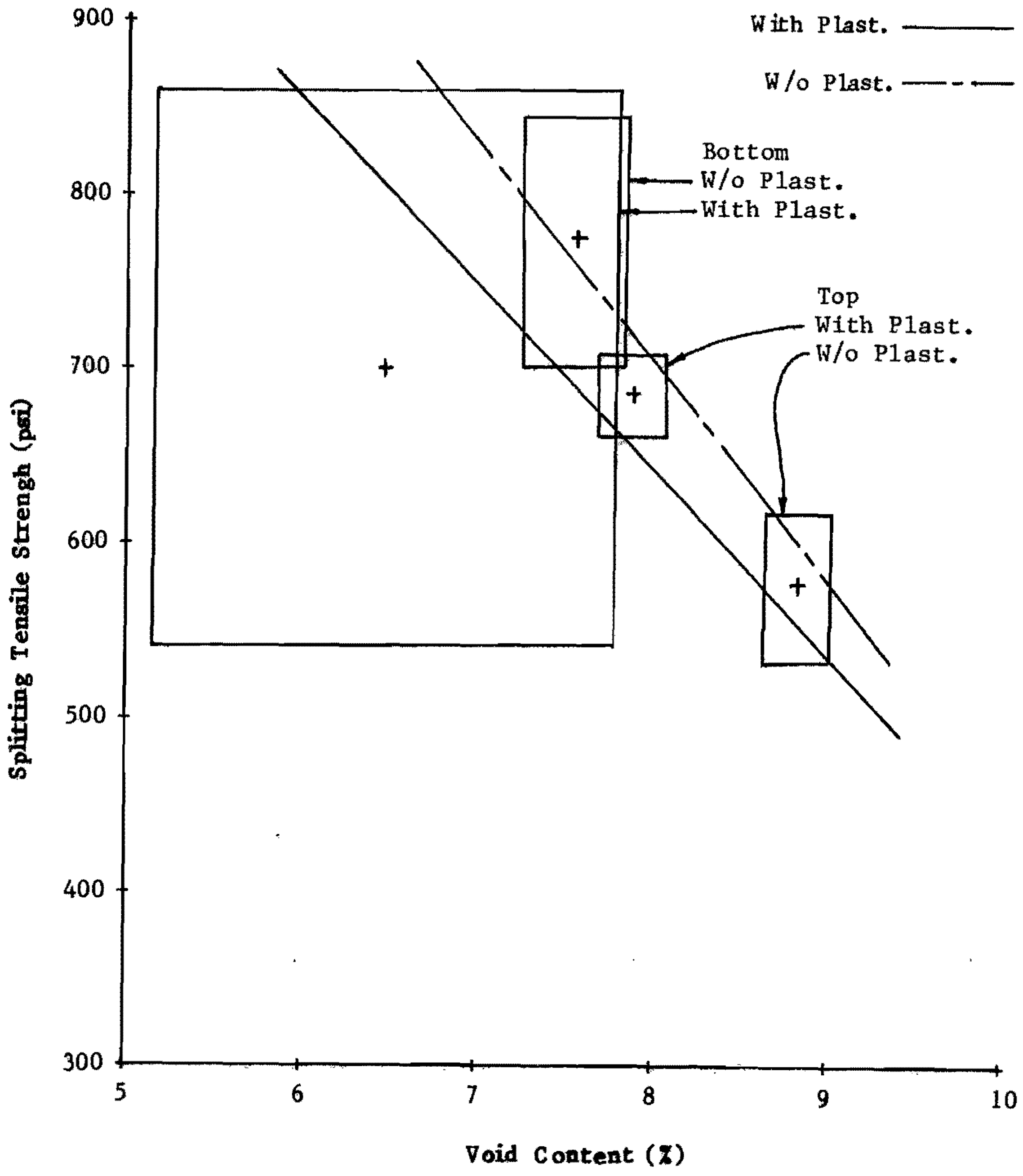
Consolidation vs. Superplasticizers (with and without Set Retarders)

This study incorporated three tests to determine the effects of adding superplasticizers to a concrete batch in an effort to increase their subsequent strengths while maintaining the void content. In each case the cement contents were held consistent to previous tests (5.5 sk/cy) and the water was reduced in order to meet the slump requirements of slip-form paving. Two of the three tests were performed using a superplasticizing agent only, while the third test incorporated the use of a superplasticizer that also contained a set retarding agent. The two tests conducted with only a superplasticizing agent were vibrated differently; one test had two vibrators spaced at 18 in. and the other had one vibrator turned perpendicular to the direction of travel. The test that used the set retarder with the superplasticizer had a vibrator mounted perpendicular to the direction of travel.

The basis for comparison was again to determine the relationship of void content vs. splitting tensile strength. Since the concrete was vibrated differently in these three tests (one with the vibrators spaced at 18 in. and the others with a vibrator perpendicular to the direction of travel) two analyses had to be made.

Figure 16 (p. 54) depicts the relationship of splitting tensile strength vs. void content for the test with superplasticizer and an 18 in. spacing. The results of this test have been compared to test no. 1 where no plasticizing admixture was used and the vibrators were also spaced at 18 in. As noted in Figure 16 (p. 54), the linear regression lines had a very similar slope, however, the concrete that contained the superplasticizer appears to have a slight shift of the line toward the origin. This finding is completely contrary to what should be expected. The test using the superplasticizer allowed for a significant

Figure 16. **Effect of superplasticizers on splitting tensile strength vs. void content.**



Note: Tests conducted with an 18 in. vibrator spacing and 1-1/2 in. maximum aggregate size. The lines are linear regressions, and each box denotes mean values +/- one standard deviation.

lowering of the water/cement ratio, which should result in an increase in strength at a given void content. Therefore, one would expect the linear regression line to shift outward from the origin rather than inward.

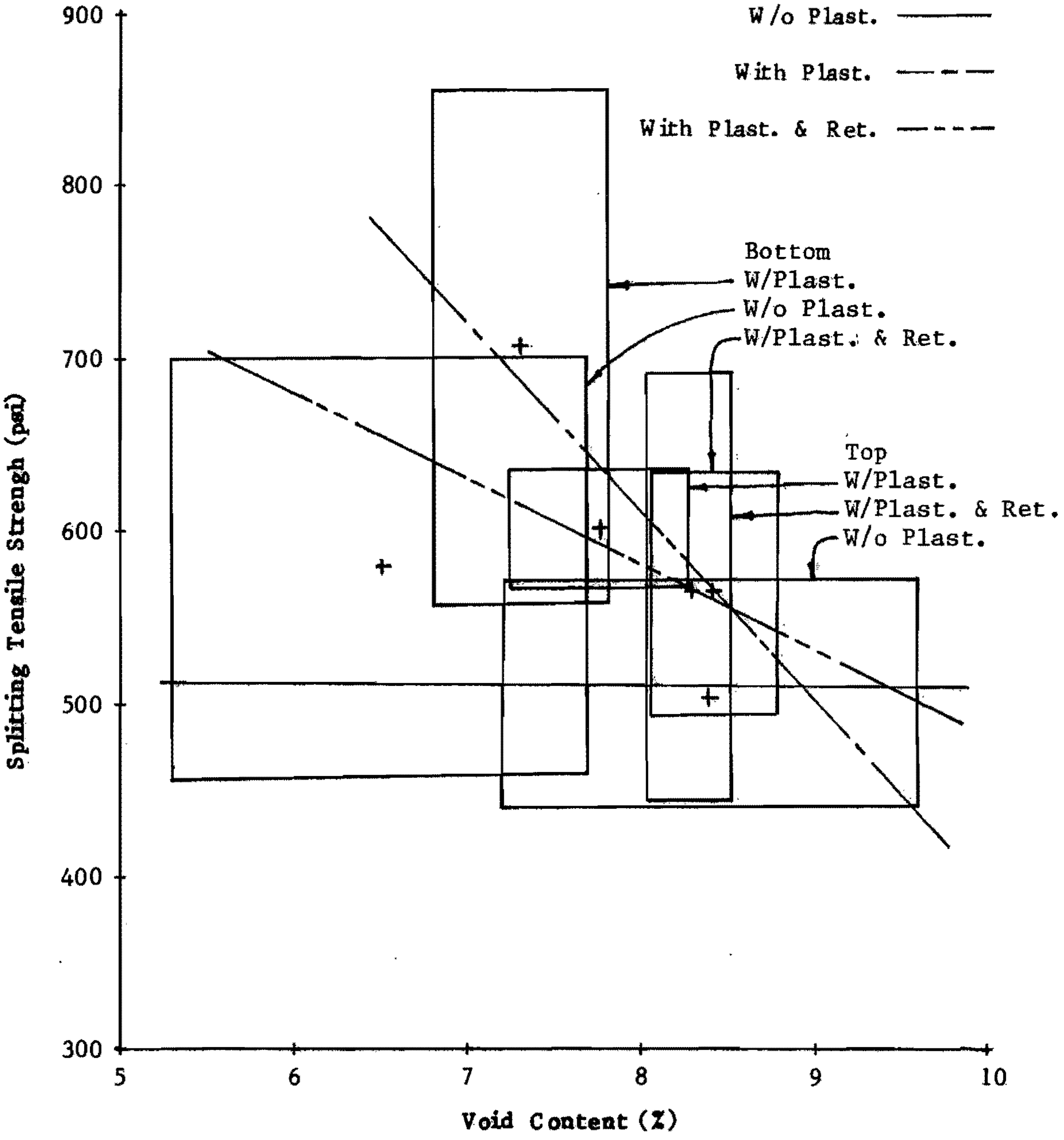
A visual examination of the concrete slabs containing the superplasticizer revealed that the actual void contents were probably much higher than was provided by the ASTM test. While the concrete was strong (see the strength results in Appendix D), it had not received adequate consolidation, and large honeycombs were visible throughout the slabs. The problem was traced to the incredible slump loss experienced during the batching procedure. By the time the fourth batch was mixed and placed in the forms, the first batch was nearly too stiff to vibrate. It took comparably more force to pull the vibrators through this concrete than any of the concrete that had not been subject to superplasticizer.

Figure 17 (p. 56) reveals the relationship of splitting tensile strength vs. void content for the tests using superplasticizer with and without a set retarder and a vibrator mounted perpendicular to the direction of travel. The results of these tests have been compared to the test where no plasticizer was used and the vibrator also traveled perpendicular to the direction of travel.

Once again it was found that this method of mounting the vibrators yields very erratic results. The linear regression lines showed very little information since the data was all grouped so closely, and the correlation coefficients were low. A visual examination of the concrete in the two tests where superplasticizer was used (both with and without a set retarder) revealed that the void content data was once again suspect. It appeared that, due to the large honeycombing visible throughout the slabs, the void contents should have been much higher than found by the ASTM test.

The set retarder did appear to aid in the vibration of the concrete,

Figure 17. Effect of superplasticizers with and without set retarders on splitting tensile strength vs. void content.



Note: Tests conducted with vibrator mounted perpendicular to the direction of travel and 1-1/2 in. maximum aggregate size. The lines are linear regressions and each box denotes mean values +/- one standard deviation.

however, the forms could not be removed for nearly a week. The concrete would not set and could easily be chipped and deformed. It was apparant that the proportion of set retarder to superplasticizer used was much too high.

The inherent problem of using superplasticizers, the rapid rate of slump loss, was the key to the failures of this portion of the testing procedure. The concrete simply would not remain workable long enough for it to be placed and vibrated. The addition of the set retarders appeared to help, but since the proportioning was so poor, the degree of this aid cannot be determined.

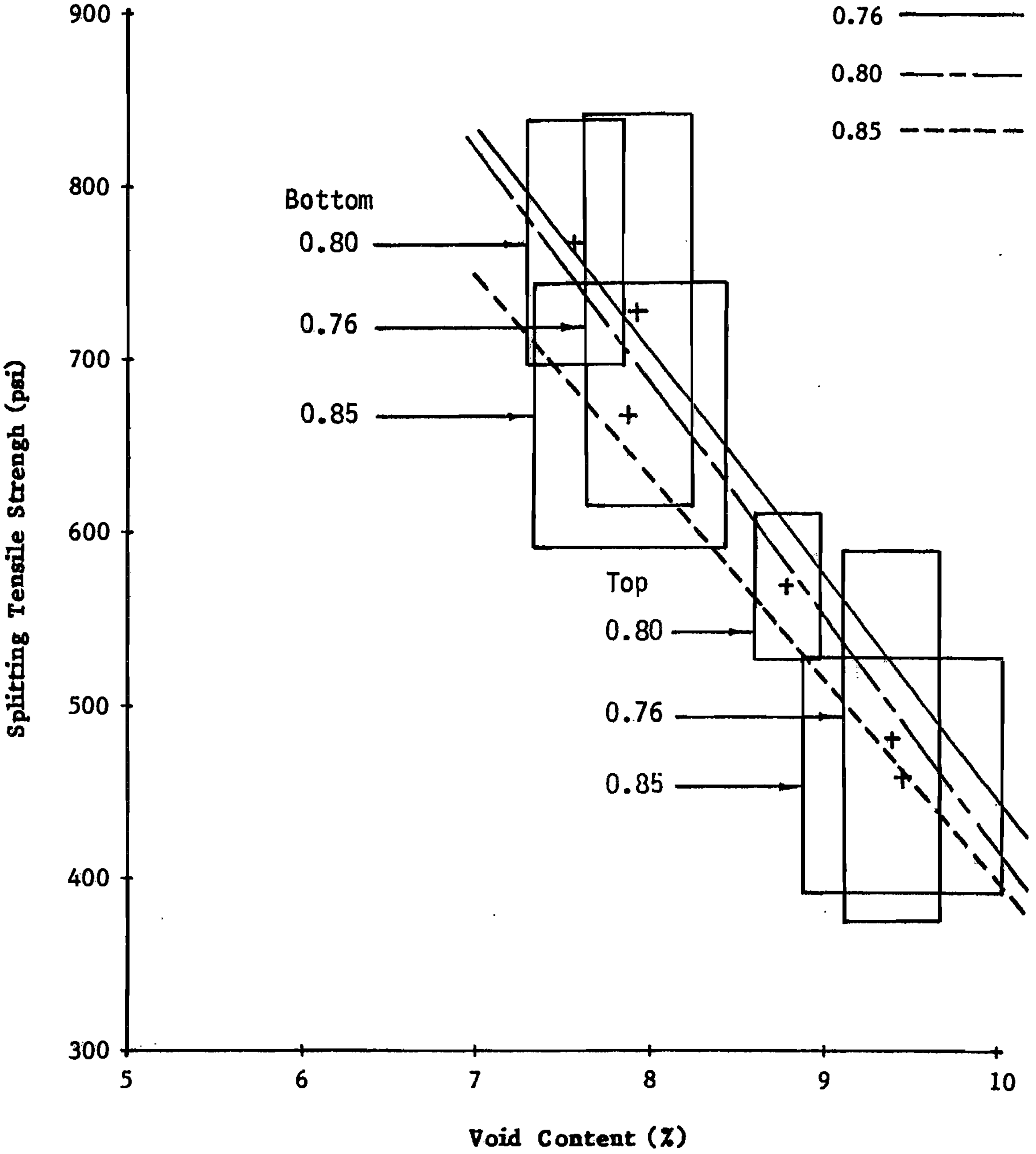
In summary, more needs to be learned about controlling the effects of superplasticizers before they can be incorporated into slip-form paving construction. Superplasticizers, even with set retarders do not aid in consolidation. They may be used to create stronger concrete at a given void content, but from these tests do not show any potential for allowing the concrete to be better consolidated at a fixed level.

Consolidation vs. Coarse Aggregate Factor

Currently, the SDHPT specifies the upper limit of the coarse aggregate factor to be 0.85. Part of the testing program included in this study was designed to determine the consequences of varying the coarse aggregate factor on achieved consolidation. Coarse aggregate factors of 0.76, 0.80, and 0.85 were used to measure this variability.

Figure 18 (p. 58) presents the relationship of splitting tensile strength vs. void content for the three tests performed with the different coarse aggregate factors mentioned. A close examination of the linear regression lines revealed that they had the same basic slope, meaning that tests with each coarse aggregate factor experienced approximately the same change in splitting tensile

Figure 18. Effect of coarse aggregate factor on splitting tensile strength vs. void content.



Note: Tests conducted with an 18 in. vibrator spacing and 1-1/2 in. maximum aggregate size. The lines are linear regressions, and each box denotes mean values +/- one standard deviation.

strength for a given change in void content.

Also of importance from Figure 18 (p. 58) was the position of the linear regression lines with respect to one another. The lines moved outward from the origin as the coarse aggregate factor was decreased. This meant that for a given level of consolidation (void content) the 0.76 coarse aggregate factor yielded the highest splitting tensile strength, then the 0.80, and finally the 0.85 yielded the lowest strength. This effect was slightly more pronounced as the coarse aggregate factor was increased from 0.80 to 0.85. However, note that these linear regression lines fall very close to one another and the inclusion of a 95% confidence interval about each one would lead to an overlap in all cases.

While the findings determined thus far were important, they yielded no information about the degree of consolidation attainable for a given coarse aggregate factor. For this reason, an examination had to be made to determine where the results were concentrated along the linear relationship between splitting tensile strength vs. void content. The boxes in Figure 18 (p. 58) showed that the 0.80 coarse aggregate factor resulted in more adequate consolidation and exhibited less data scatter when subject to the same degree of vibration. The 0.76 and 0.85 coarse aggregate factors yielded almost identical void content results (with the 0.76 coarse aggregate factor having a higher strength than the 0.85 coarse aggregate factor). This is interesting and perhaps could be traced back to the theory discussed in relation to Figure 4 (p. 15). According to this principle, the 0.85 coarse aggregate factor might correspond to Figure 4a (p. 15), the 0.80 coarse aggregate factor might correspond to Figure 4b (p. 15), and the 0.76 coarse aggregate factor might correspond to Figure 4c (p. 15). This would lead one to believe that the 0.80 coarse aggregate factor is the optimum ratio of the bulk volume of coarse aggregate to the total volume of concrete for the gradation shown in Appendix A. If the gradation of the coarse and fine aggregate is changed a different optimum coarse aggregate factor might result. Any coarse aggregate factor less than 0.80 would lead to an abundance of fines and the problems associated with this, and any coarse aggregate factor greater than 0.80 would lead to a concrete mixture lacking enough fines to fill the voids between all of the coarse aggregate.

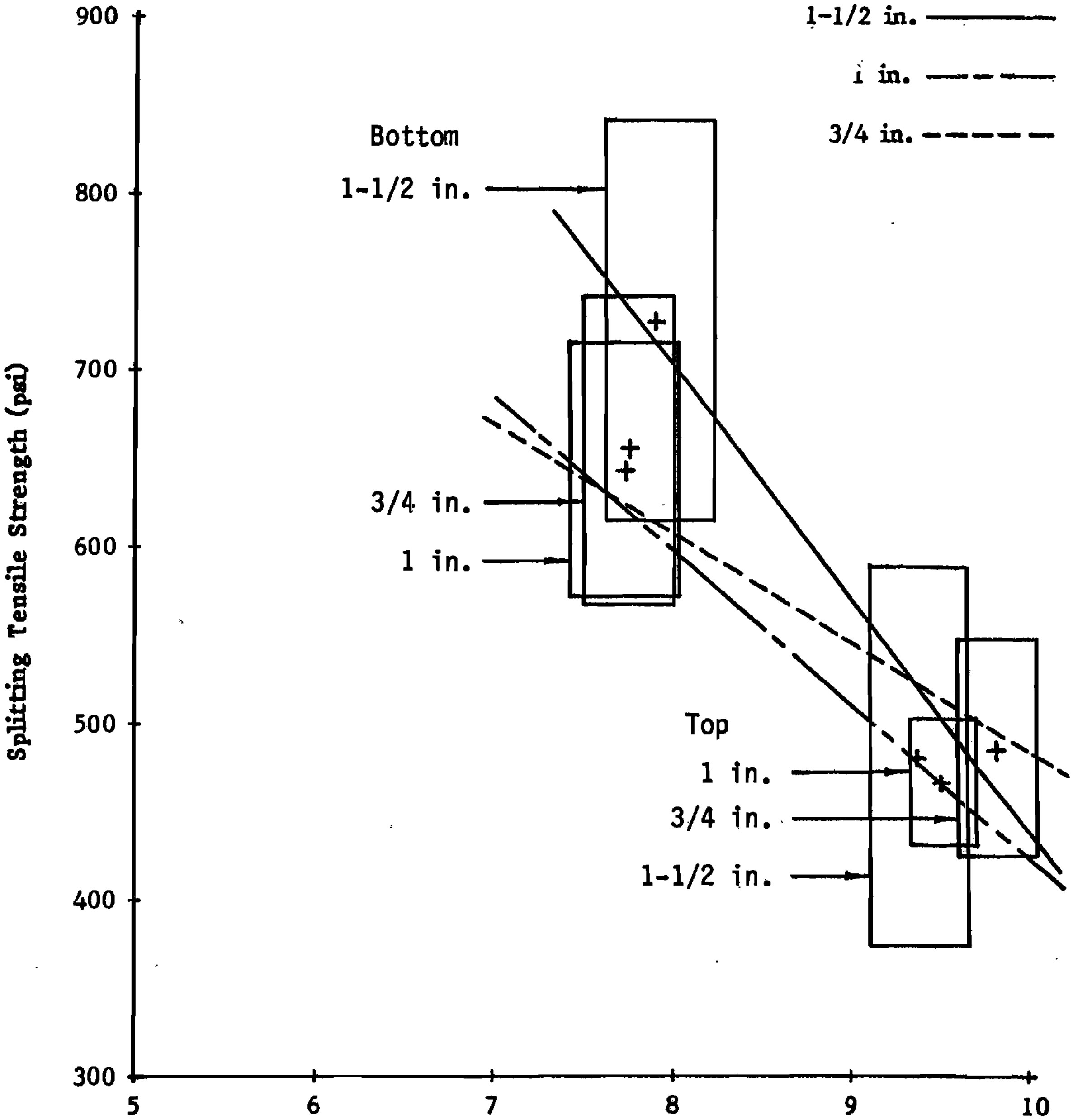
The use of the Fineness Modulus Method of mix design provided this same conclusion. By using the information provided in Appendix A and going through the calculations necessary in the Fineness Modulus Method of mix design, it was determined that the 0.80 coarse aggregate factor should produce the best concrete. This method of choosing the optimum coarse aggregate factor appears to be the most practical procedure for predicting the best proportions of the aggregates to use.

Consolidation vs. Coarse Aggregate Size

The testing program for this study included a comparison of concrete tests that incorporated maximum sizes of the coarse aggregate of 1-1/2, 1, and 3/4 in. The objective of this comparison was to determine the relation of void content to splitting tensile strength for the various maximum aggregate sizes, and to determine which aggregate size resulted in the highest degree of consolidation for a given consolidation effort.

Figure 19 (p. 61) reveals the results of data accumulated from the tests conducted with each of the mentioned maximum aggregate sizes. An examination of the linear regression lines revealed two important relations. First, there was a definite slope change from one aggregate size to the next. As the maximum aggregate size was increased, the resulting splitting tensile strength was increasingly influenced by changes in the void content. A change in the void content would influence the strength of the concrete containing the larger

Figure 19. Effect of coarse aggregate size on splitting tensile strength vs. void content.



Note: Tests conducted with 0.76 coarse aggregate factor and an 18 in. spacing of the vibrators. The lines are linear regressions, and each box denotes mean values +/- one standard deviation in each direction.

aggregate much more than it would concrete made with smaller aggregate.

The second important relation that could be taken from the linear regression lines included in Figure 19 (p. 61) was the relative position of the regression lines to one another. It was clear that below a void content of about 9% the 1-1/2 in. aggregate resulted in the highest splitting tensile strength for a given void content. This could be attributed to the phenomenon mentioned earlier, in that the larger aggregate mix required less water than the mixes made with the smaller aggregate. Furthermore, the amount of data scatter made it impossible to determine what differences in strength occurred between coarse aggregate sizes of 1 and 3/4 in.

To determine the effects of a given consolidation effort it was necessary to examine the position of the data concentrations (the boxes) along the linear regression lines. From this information, it could be seen that the consolidation effort imparted on the various test conditions resulted in relatively the same degree of consolidation regardless of the maximum aggregate size. Most all of the data fell in the same place along the void content axis. Consolidation was not influenced by aggregate size within the range of 3/4 in. to 1-1/2 in. The important thing to note was that almost all of the data fell below a 10% void content. By combining this information with that already discussed, it could be concluded that the 1-1/2 in. maximum size aggregate was the most desirable. This choice of aggregate should result in the maximum consolidation and the highest strength attainable.

One argument could possibly be presented in an attempt to refute this conclusion. Since the slopes of the linear regression lines revealed that the concrete containing the 1-1/2 in. aggregate was more sensitive to strength change due to a change in void content and had more data scatter, it would be more reasonable to limit the maximum allowable coarse aggregate size to 1 in.

While this argument has its merit, it does not appear to be significant enough, within the range of the findings, to offset the initial conclusion to choose the larger aggregate. An increase in voids in the bottom of the slab of about 1% void content would be necessary in the concrete containing the 1-1/2 in. aggregate in order to achieve strengths similar to the concrete containing the smaller aggregate.

Additional consideration of the economic effects involved in choosing an appropriate maximum aggregate size, also led to the conclusion that the 1-1/2 in. aggregate was the most desirable. Since the aggregate used in these tests was crushed aggregate, a reduction of the maximum size would have resulted in an increase in production costs due to the increased amount of crushing necessary.

Consolidation vs. Acceleration

This study incorporated in its testing program a method of determining the levels of acceleration applied to the concrete by the vibrators as they moved through the fresh concrete. It was the objective of this part of the study to determine if accelerations could be monitored and recorded during the consolidation process, and if these readings could be used to describe the effects of a given consolidation effort on a concrete mix. The results of the acceleration readings for tests 2, 3, 4, 6 and 7 can be found in Figures 20 through 29 (pp. 64-73).

A few problems were encountered in the recording of the acceleration data. During a number of the tests, problems were experienced in the elaborate network of instruments necessary to record the data. Due to a lack of sufficient personnel available to insure that the instruments were in proper working order,

Figure 20. Accelerometer readings for test 2 (above and below no reinforcement).

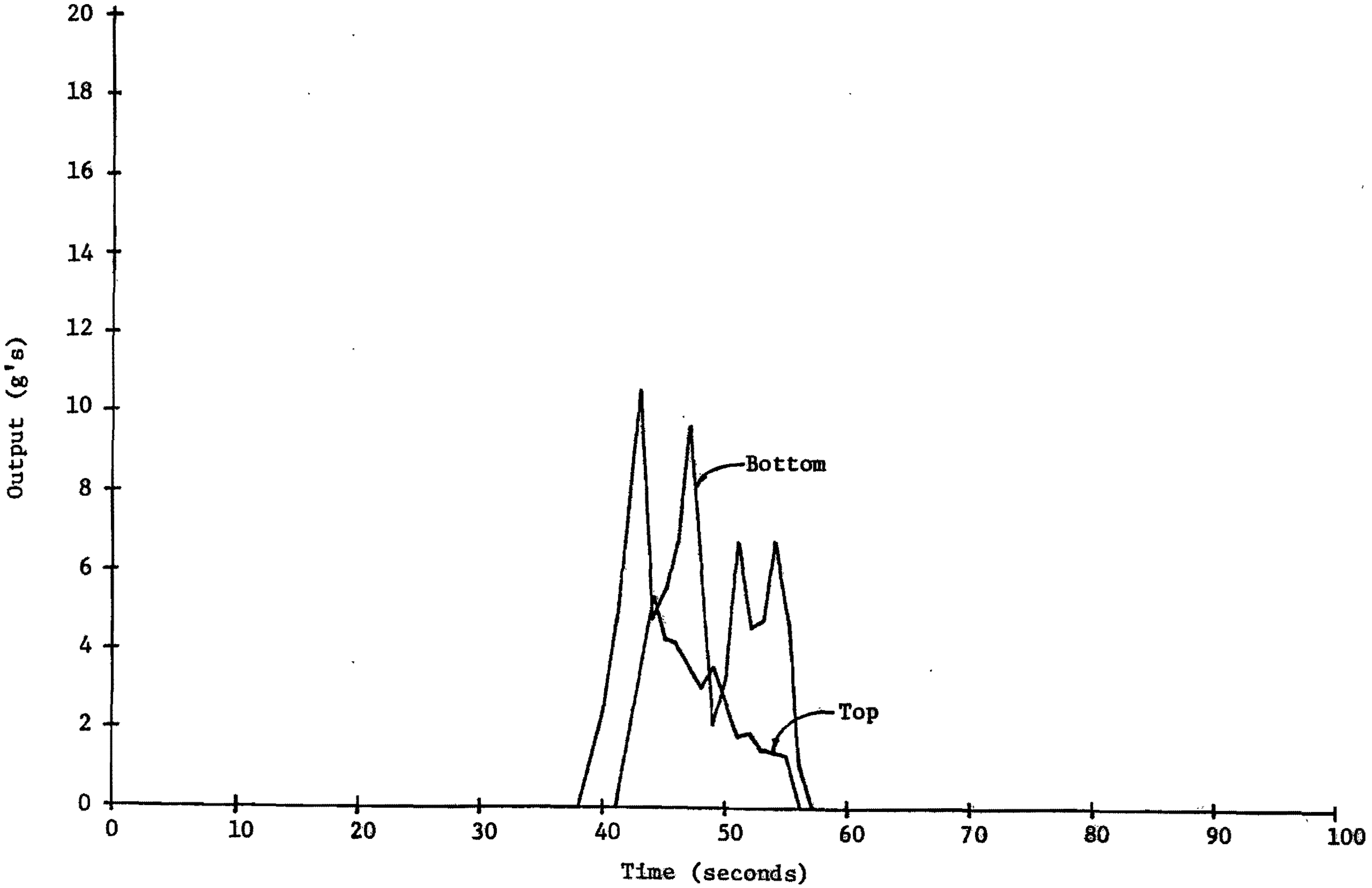


Figure 21. Accelerometer readings for test 2 (above and below the crossing of two reinforcing bars).

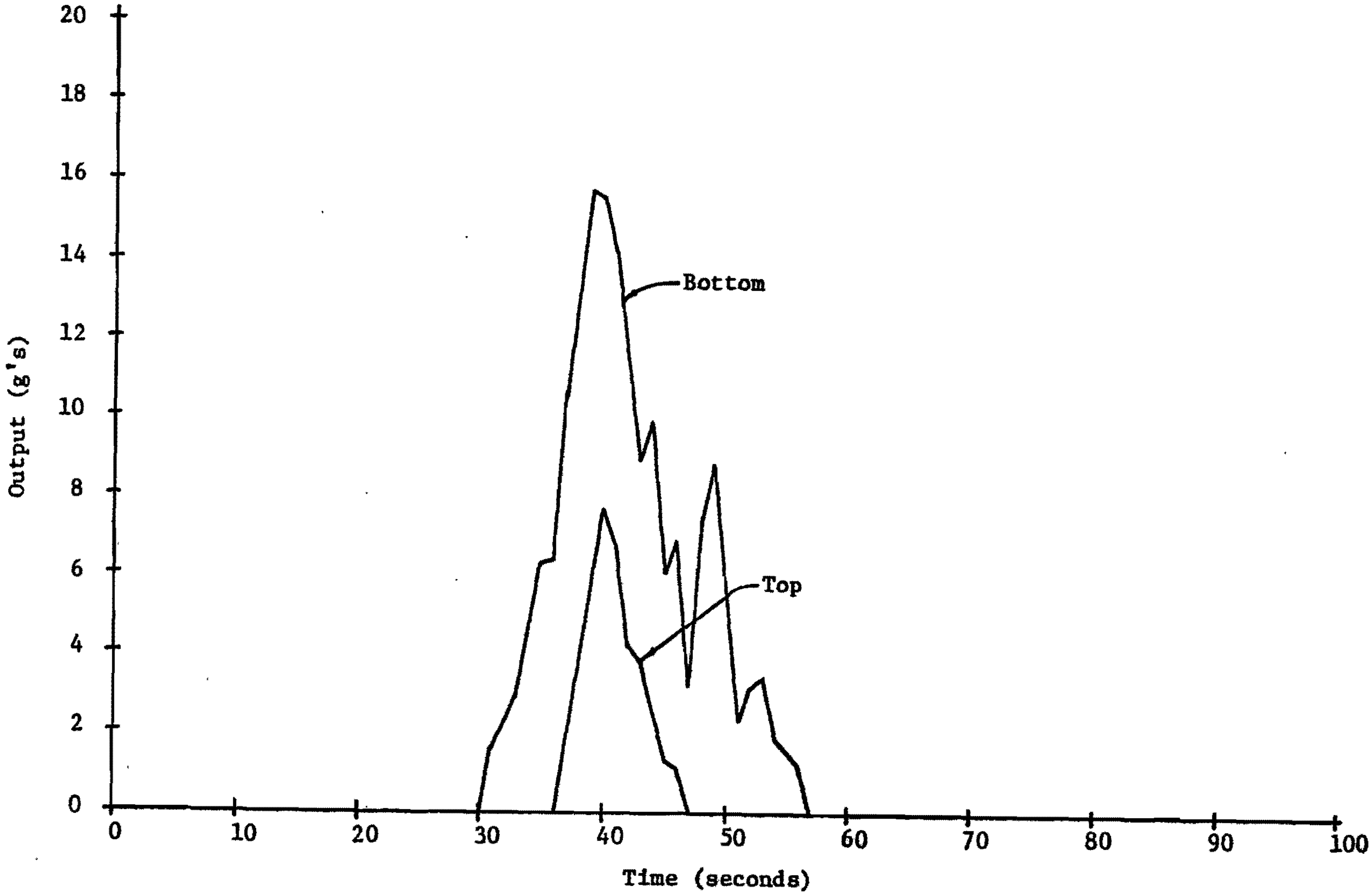


Figure 22. Accelerometer readings for test 3 (above and below no reinforcement).

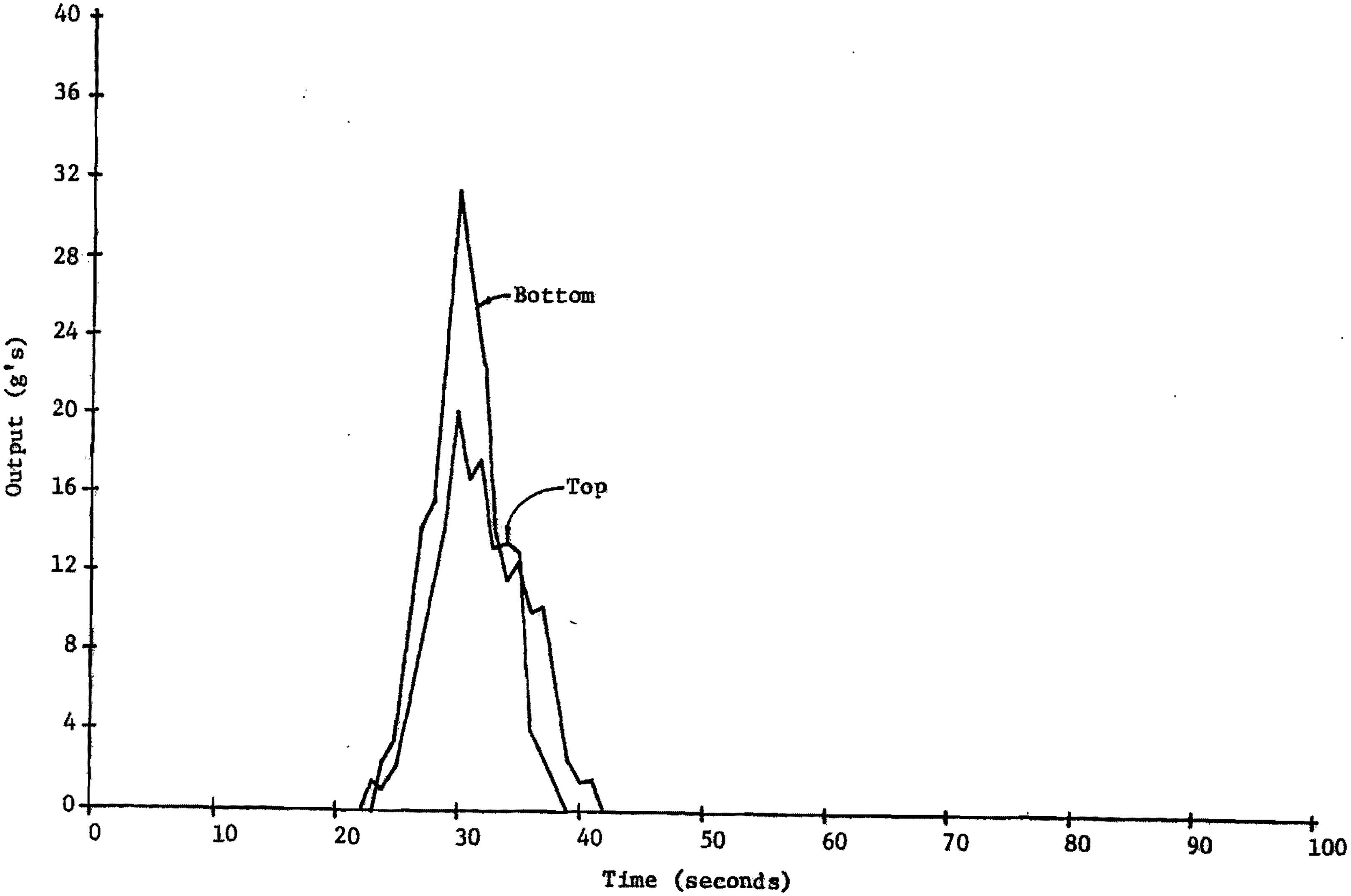


Figure 23. Accelerometer readings for test 3 (above and below the crossing of two reinforcing bars).

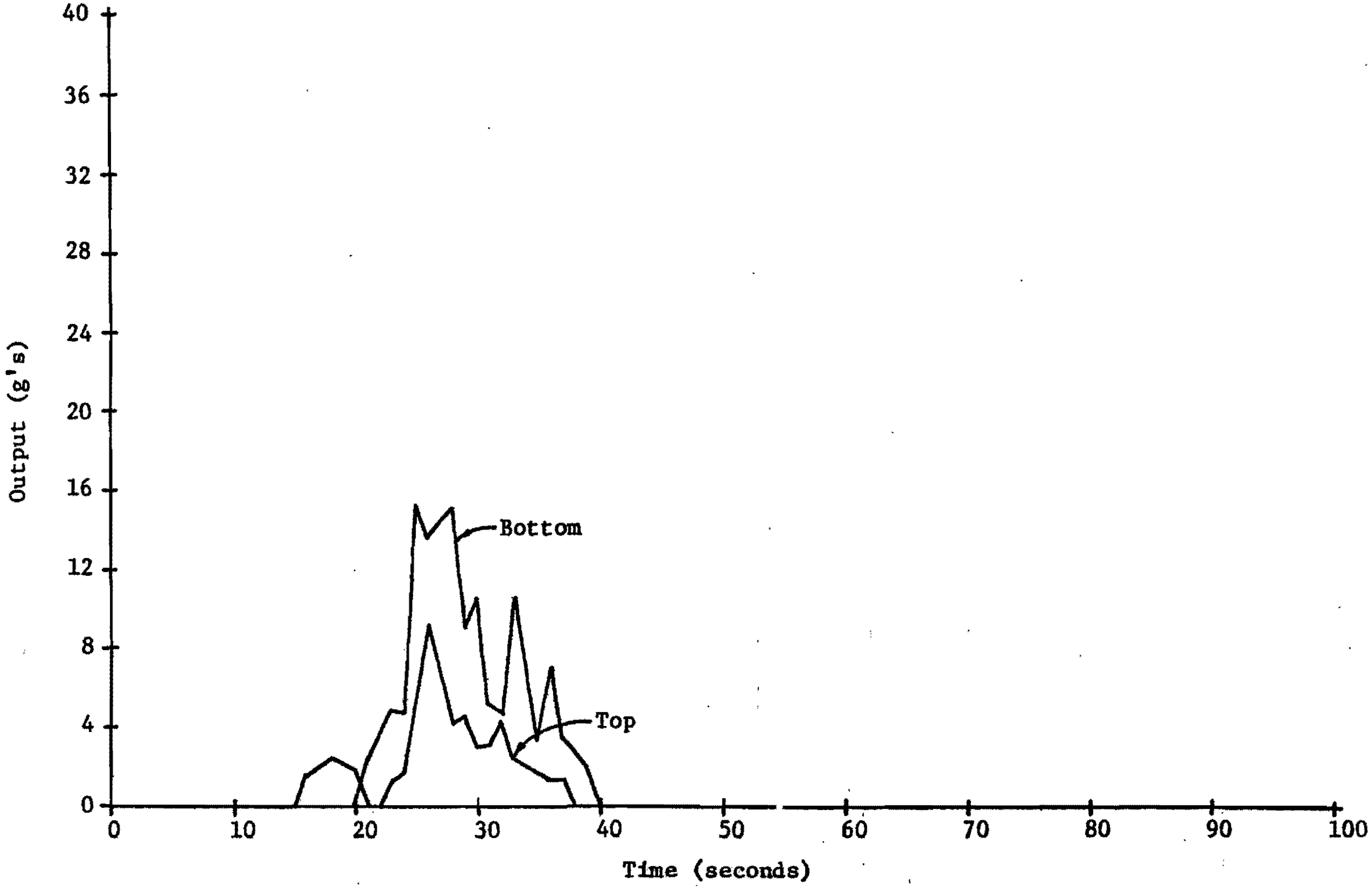


Figure 24. Accelerometer readings for test 4 (above and below no reinforcement).

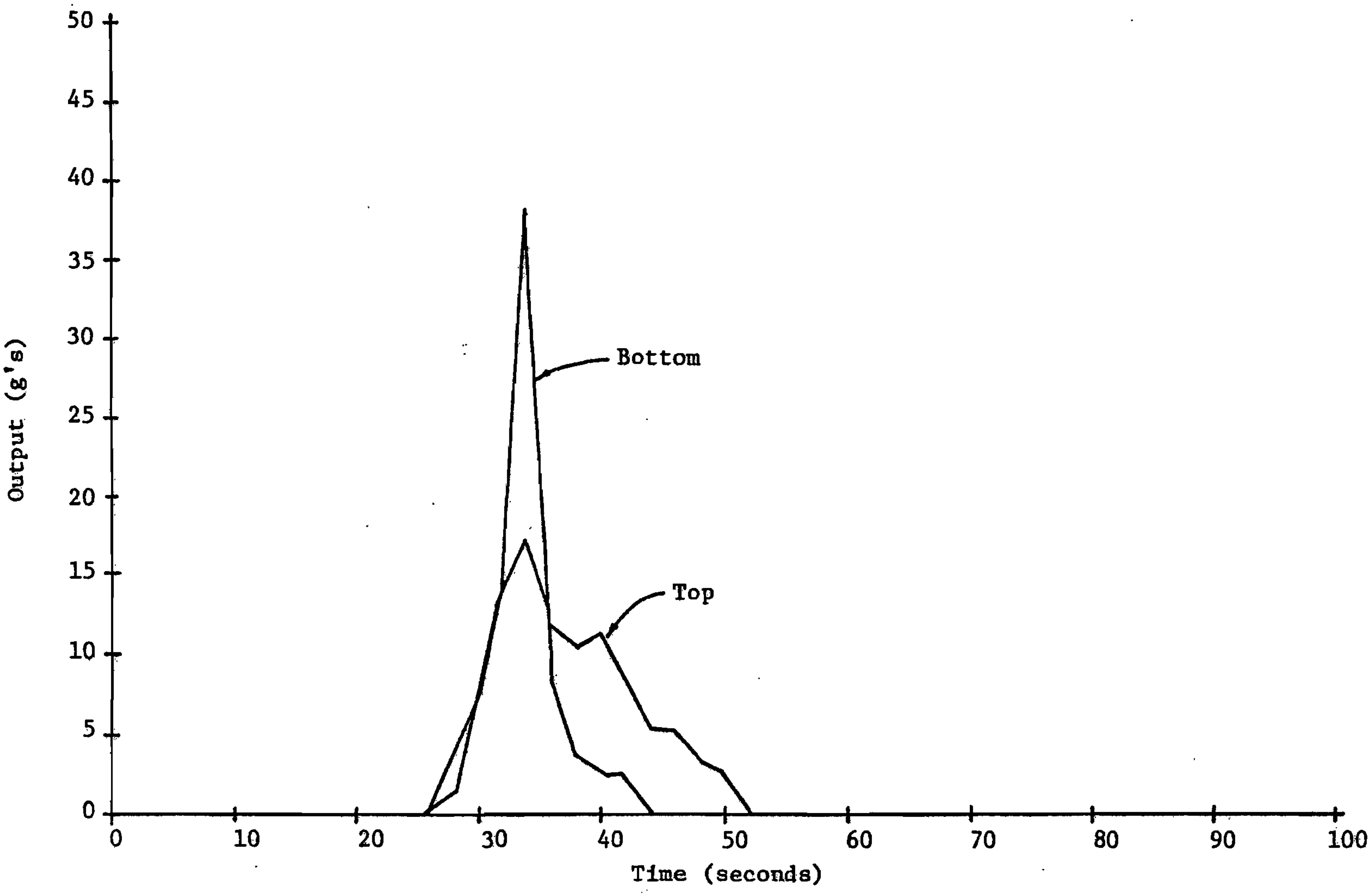


Figure 25. Accelerometer readings for test 4 (above and below the crossing of two reinforcing bars).

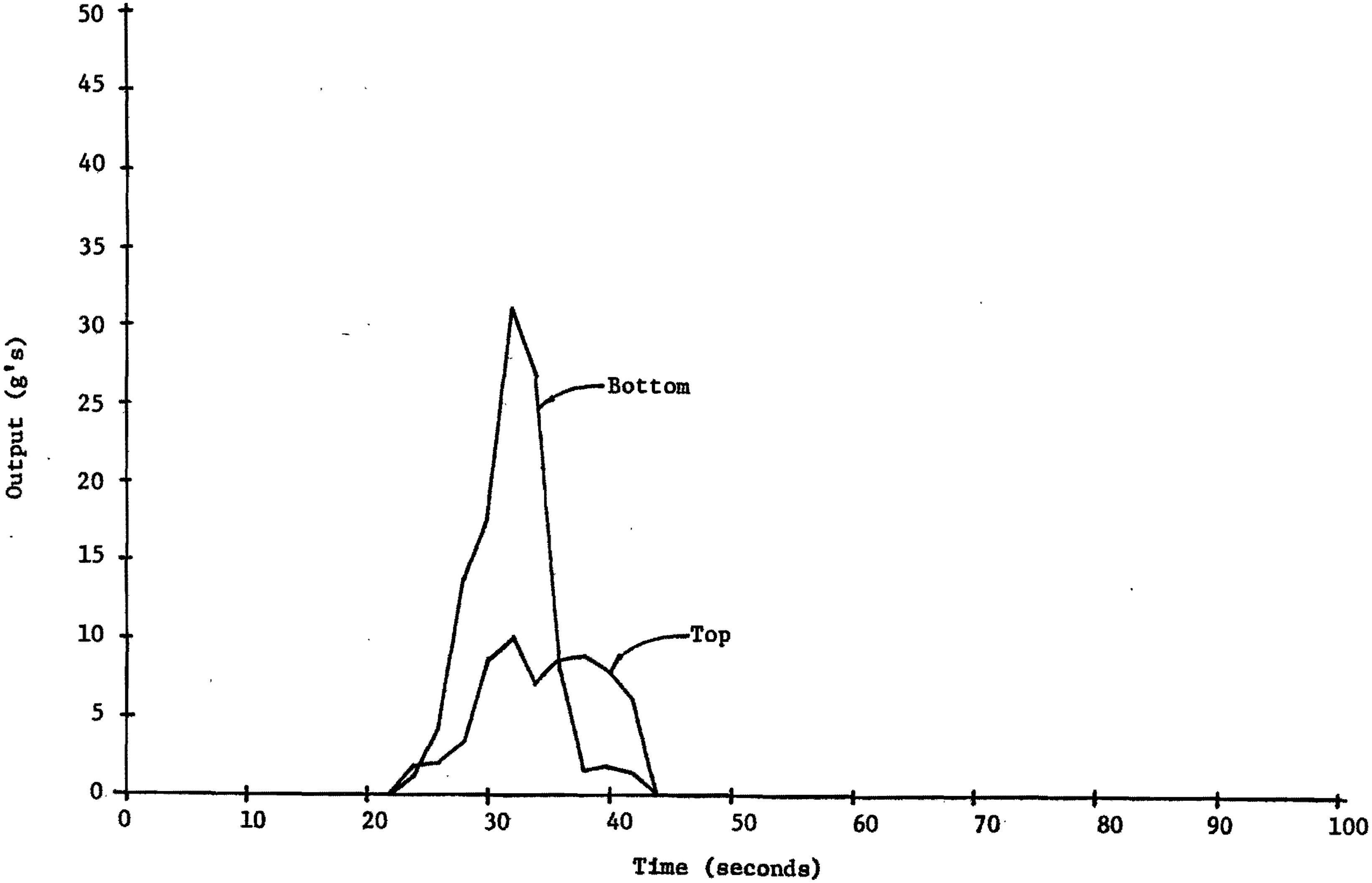


Figure 26. Accelerometer readings for test 6 (below no reinforcement).

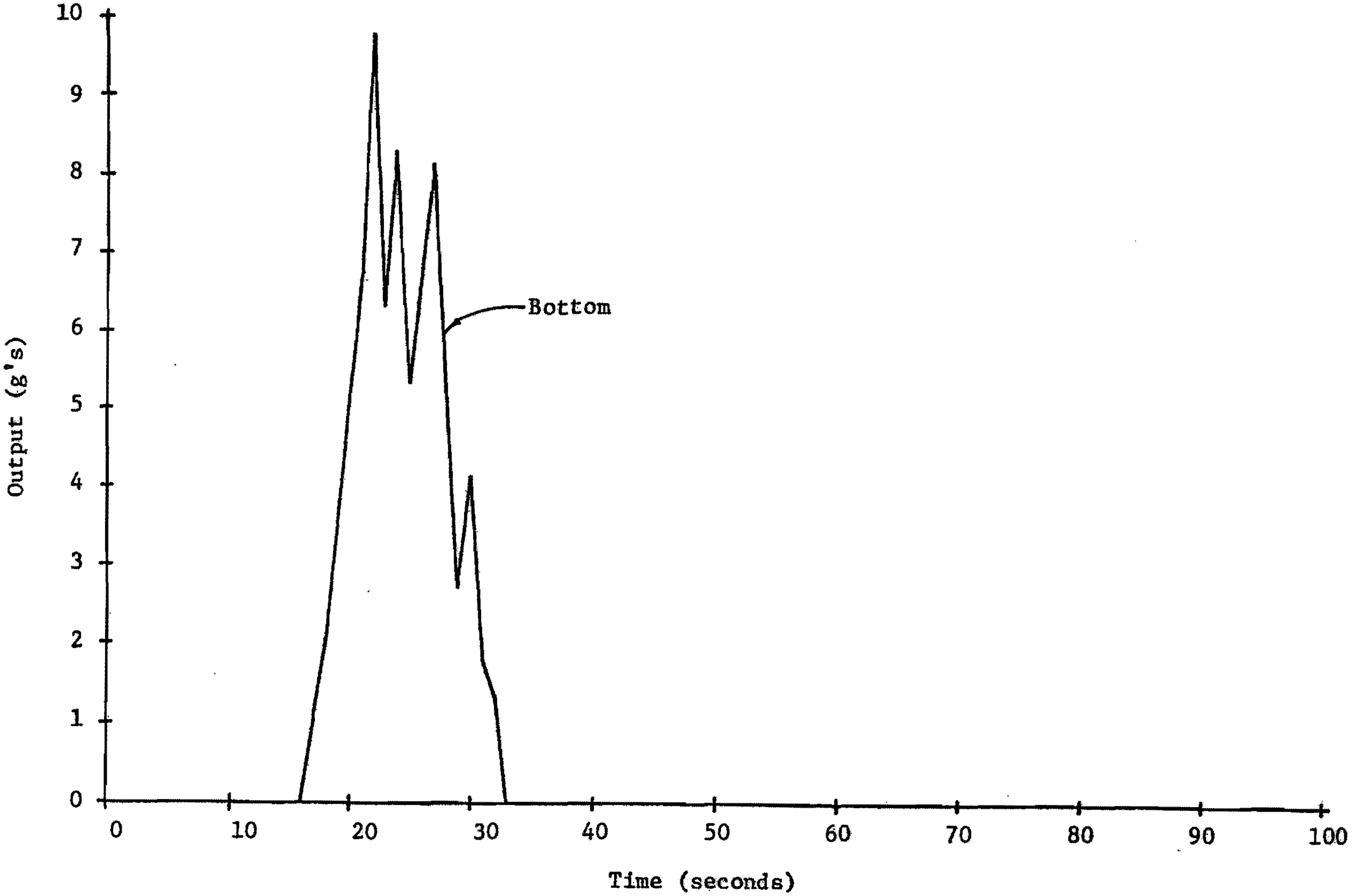


Figure 27. Accelerometer readings for test 6 (above and below the crossing of two reinforcing bars).

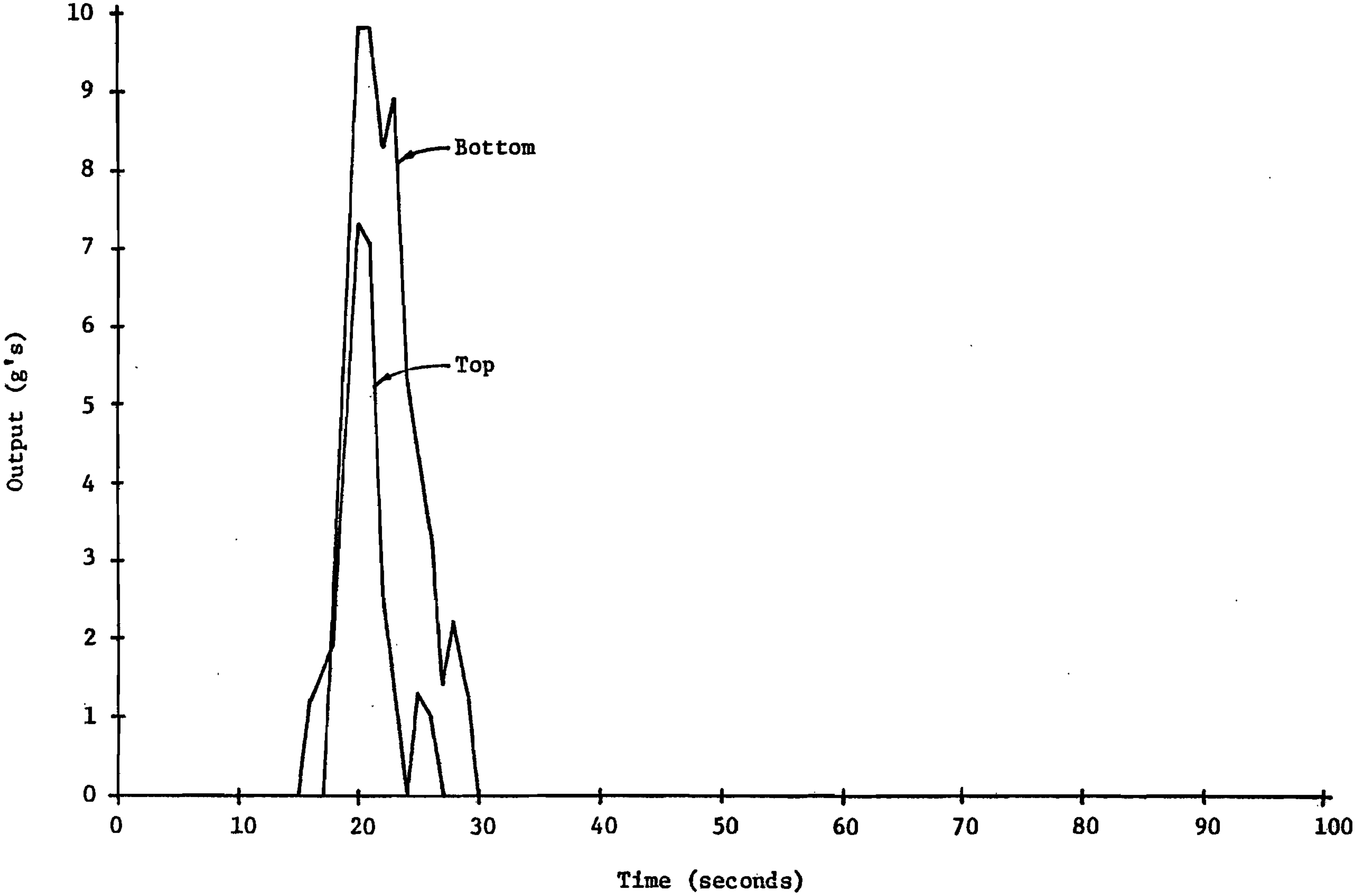


Figure 28. Accelerometer readings for test 7 (below no reinforcement).

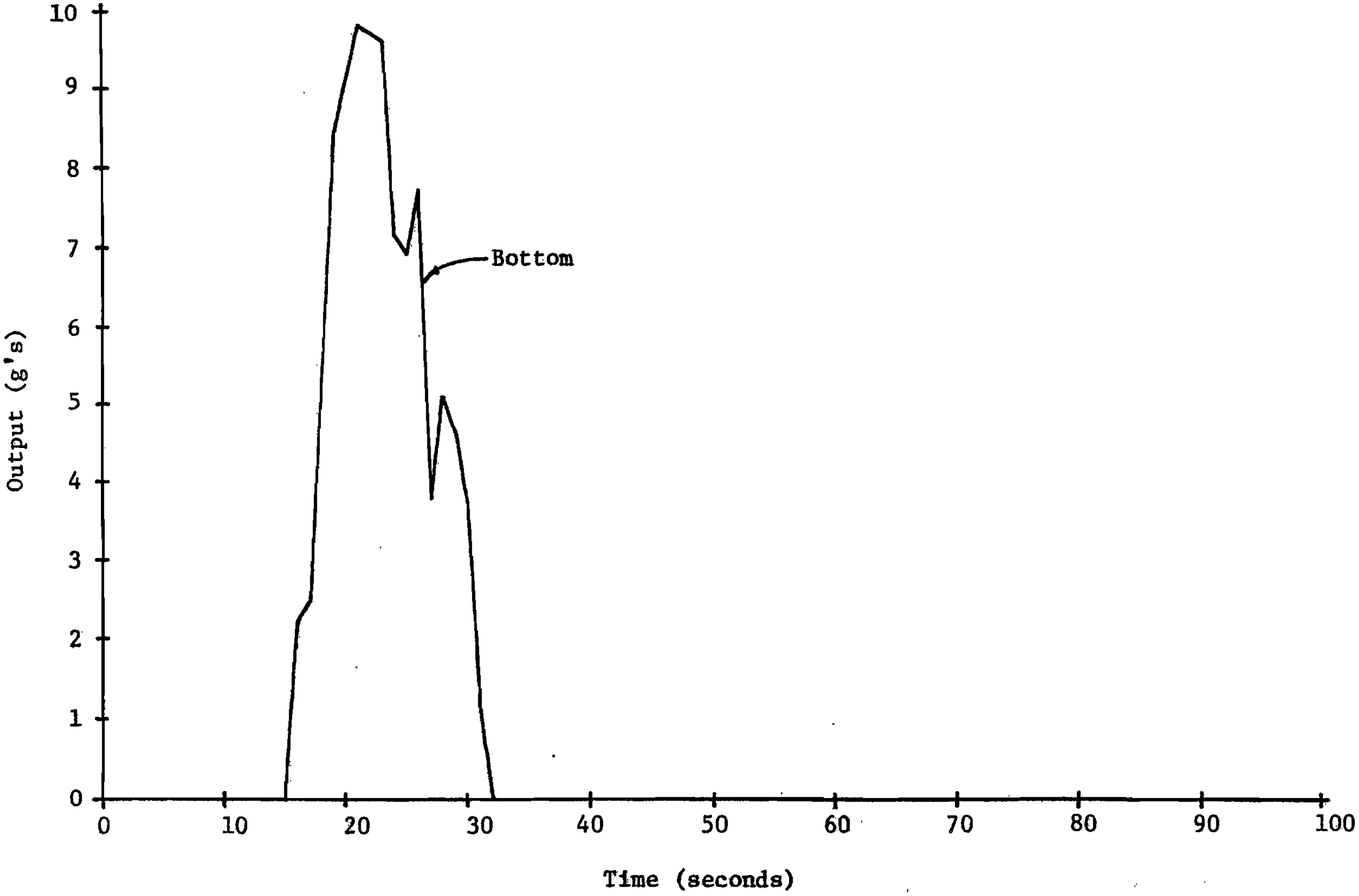
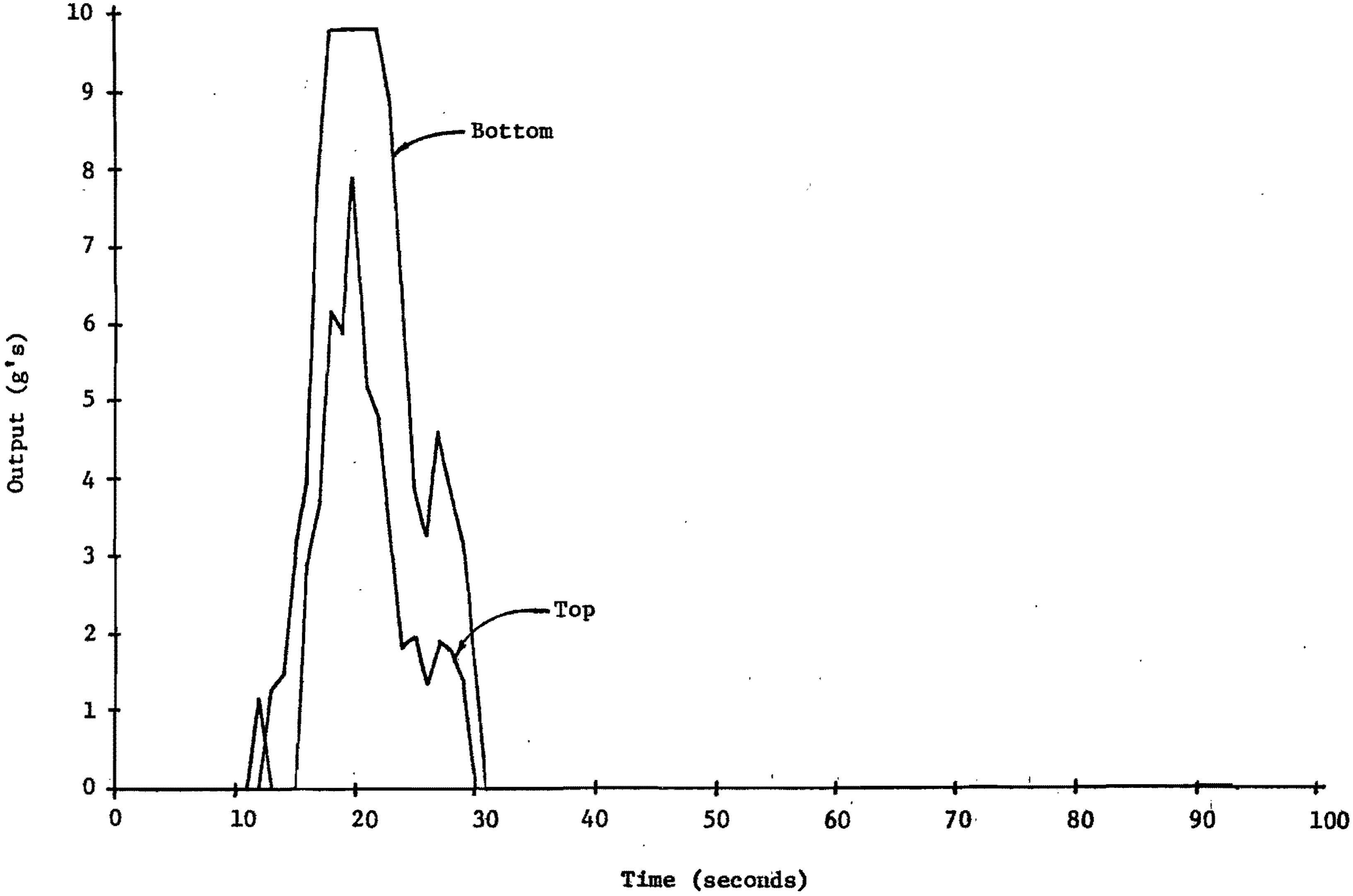


Figure 29. Accelerometer readings for test 7 (above and below the crossing of two reinforcing bars).



the importance of time once the concrete batching operation began, and the fact that the ability to take acceleration readings was given the lowest priority during testing, some of the tests did not result in a complete set of data, and some tests did not result in any data readings at all. However, the results that were obtained provided some very interesting information.

It was quickly noticed, after viewing the graphs of time vs. acceleration output, that there was a general trend to most of the curves; especially the graphs of the tests where consolidation was noticed to occur with the greatest ease during the casting operation (See Figures 20, p. 64; 21, p. 65; 22, p. 66; 23, p. 67; 26, p. 70; 27, p. 71; 28, p. 72; and 29, p. 73). It appeared that the concrete remained practically stationary until the vibrator approached a position almost directly above, or below, the accelerometers. At this time the acceleration of the concrete particles increased almost immediately to the peak. Afterwards, it appeared that the curves took on some type of wave form, probably associated with the vibrational waves transmitted through the mortar in the mix.

This finding can be related to what is known to occur during the consolidation process. As the vibrator approaches, the concrete remains stiff until the forces become great enough to overcome the internal friction of the mix. At this time, the mortar begins to transmit the vibrations and allows the solids to settle while the air rises to the surface. It is this stage of the consolidation process that must be allowed to continue in order to relieve the mix of all the entrapped air voids.

Therefore, once the concrete had its initial slumping, the distance along the x-axis of the curve was of extreme importance in determining how much air was allowed to escape. The results of the test performed where the vibrators were spaced at 24 in. (see Figure 21, p. 65) probably depicted the effect best.

It could be seen in this Figure that the bottom of the slab was receiving the highest degree of acceleration. This was not surprising since the particles being accelerated had to overcome the acceleration of gravity in order to register a reading on the accelerometer mounted on the top of the slab. The next item of interest on Figure 21 (p. 65) was the shape of the curves. Both of them peaked very rapidly, and they appeared to pick up a wave form. Since each point on this graph was an average of six recorded data points, the exact shape of the wave form could not be shown.

Exactly what information could be derived from this graph had to be determined. Since the accelerometer was actually measuring the acceleration of particles in the concrete, a review of particle dynamics helped to develop an angle of study. The area under the curve on the graph yielded the velocity of the particles in motion:

$$\int_{t_1}^{t_2} a(t)dt = v(t)$$

The linear momentum (p) of a particle is defined as the product of its mass (m) and its velocity (v(t)); therefore:

$$p = m * v(t)$$

The total energy of a particle in motion (E) is equal to the sum of its kinetic energy and its potential energy; therefore:

$$E = (1/2 * m * v(t)^2) + (m * g * y)$$

By assuming mass, gravity (g), and vertical distance (y) to remain constant from one mix to another, it could be said that the energy imparted on the concrete by a vibrator was a function of the acceleration of the particles. Therefore, the area under the curve yields a reference for determining the energy produced on a concrete mix under vibration.

Table 4 shows the results of the relative energy produced on the concrete mixes under vibration and the degree of consolidation achieved for test numbers 1 through 7 and number 9 in the laboratory and for tests 1 and 2 in the field (State Highway 288 in Houston). In Figure 30 the Degree of Consolidation (defined as the dry unit weight of the hardened concrete divided by the measured unit weight of the fresh concrete (AASHTO T121)) is plotted against the relative energy. A variation of the degree of consolidation between 99.4 percent and 95.3 percent is observed with a decrease in energy producing a decrease in degree of consolidation as expected. From the results of the study performed by the Colorado Division of Highways, Planning and Research Division (11) it was shown that cores from pavements with poor abrasion records had densities less than 97 percent of rodded unit weight (AASHTO T121). Based on this finding the State of Colorado uses direct nuclear transmision density measurements to enforce a requirement that the concrete be vibrated to no less than 96 percent of the maximum theoretical field density. From Figure 30 and Table 4 it can be seen that only two core samples did not meet this requirement (tests 1 and 5). In addition the results shown in Figure 30 indicate that a minimum relative energy of approximately 300 ft-lb is required to yield a degree of consolidation of no less than 97 percent. Based on this conclusion five out of eight sensors in the field tests registered a relative energy input of less than 300 ft-lb (Table 4). The concrete is therefore suspected of lack of consolidation in those five cases (Tests F11, F12, F13, F14 and F22). From the results of the split tensile strength tests of the cores from these locations, field test number 1 has a mean strength of 453 psi and field test number 2 a mean strength of 365 psi. Since the standard deviations for the tests were only 6 and 35 psi respectively, this difference in mean strengths are significant enough to

Table 4. Relative Energy[1] (ft - lb) Produced on Concrete Mixes Under Vibration and Degree of Consolidation[2].

Test #	Position	Relative Energy (ft-lb)		Degree of Consolidation	
		No Steel	Steel	No Steel	Steel
1	Top		4.1	96.8	96.6
	Bottom	85.4	259.5	96.4	95.3
2	Top	145.6	143.0	97.0	96.4
	Bottom	332.2	631.9	97.1	99.3
3	Top	653.2	350.7	97.2	98.3
	Bottom	916.8	637.3	99.4	98.4
4	Top	375.4	483.7	97.3	97.7
	Bottom	456.8	368.7	98.7	98.7
5	Top		59.9	95.4	96.9
	Bottom	216.0	164.1	96.0	96.8
6	Top		111.0	96.3	96.7
	Bottom	227.5	189.5	97.4	98.2
7	Top	97.8		95.8	96.3
	Bottom	261.9	269.5	98.0	97.0
9	Top		190.8	97.4	96.0
	Bottom	353.0	264.3	97.8	97.6
F11	Bottom	262.2		95.6	
F12	Bottom		251.1		96.5
F13	Bottom		177.0		95.5
F14	Bottom		41.8		95.4
F21	Bottom	789.5		98.1	
F22	Bottom		212.1		97.2
F23	Bottom		430.6		96.9
F24	Bottom		441.5		96.3

(1) Relative Energy = 1/2 (1 lb)$v(t)^2$

(2) Based on AASHTO T121 (γ_d/γ_c)

Note: Fxy indicate field test results, where x is the test number and y is the sensor number.

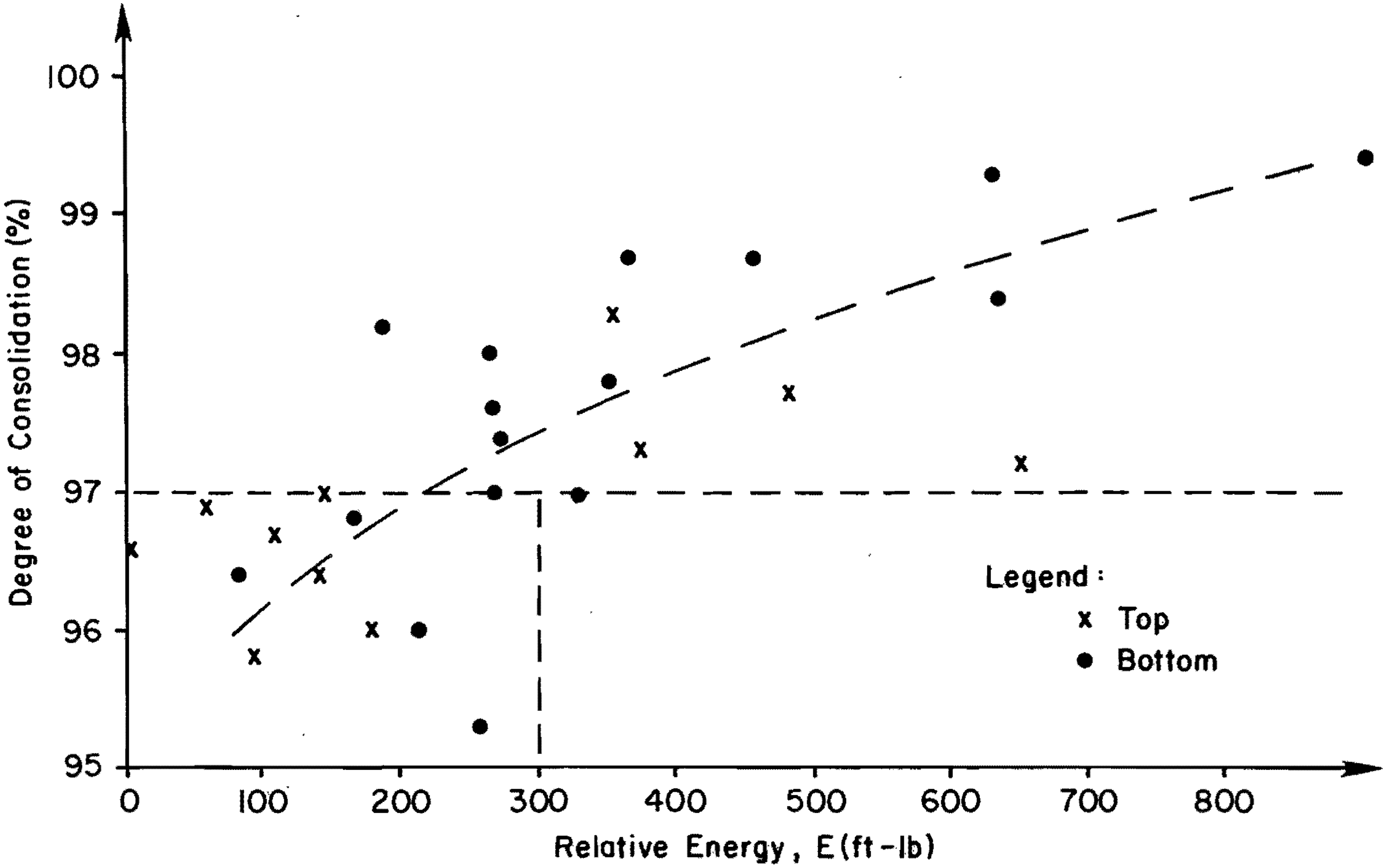


Figure 30. Degree of Consolidation (%) Versus Relative Energy (E) Produced on Concrete Mixes Under Vibration.

conclude that the two pavement sections are significantly different. The achieved consolidation levels, however, were greater in section number 2 (in average 97.1 percent versus 95.8, from Table 4). The requirement of 300 ft-lb as minimum relative energy amount seems therefore reasonable. Furthermore, based on the comparison with the data obtained in Colorado (11) field test section number 2 is expected to outperform field test section number 1 provided that the average splitting tensile strength of 365 psi also is sufficient to achieve good durability performance. The reason for the difference in the splitting tensile strengths is believed to be caused by the greater air content measured in test section number 2 (8.4 percent compared to 5.5 percent in section 1).

It was interesting to note the shape of the curves seen for the test where the vibrator was mounted perpendicular to the direction of travel (See Figures 24, p. 68 and 25, p. 69). It could be seen in this test that while there was an initial peak of the curves, there was no tailing off of the curves along the x-axis as was seen in the other test results. This could have been due to the fact that the concrete was not liquified when the vibrator passed over and the mortar never picked up the vibrations necessary to allow the air to escape. It appeared from this graph that the internal friction of the mix was either never overcome or was returned very quickly after the vibrators passed. This finding supports the findings included in the section of this Chapter that dealt with consolidation vs. the method of vibrator mounting.

Another interesting observation depicted by Figures 20 through 29 (pp. 64-73) was that the concrete particles in the top of the slab were being accelerated upward. This is not beneficial to the consolidation process, since the objective of consolidation is to accelerate the solid material downward. This effect was discussed in the section of this Chapter that dealt with consolidation versus depth in the pavement, but it should once again be emphasized. Perhaps, consideration should be given to maintaining an overburden of concrete around the vibrators and raising them above the intended depth of the slab. In this manner, all of the forces will be transmitted downward on the concrete being consolidated, and no particles will be accelerated upward. Care would have to be taken, however, to ensure that the bottom of the slab was still vibrated adequately.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following presents a summary of the conclusions made from an analysis of the literature review and the laboratory investigation. The conclusions are listed according to the specific parameter of study.

Coarse Aggregate Factor: The following conclusions were made based on the results of the literature review and three tests designed to compare the effects of a consolidation effort on concrete containing coarse aggregate factors of 0.76, 0.80, and 0.85. All other mix design and test conditions were held constant between the three tests.

1. According to theory, there should be an optimum coarse aggregate factor for a given set of materials used in a concrete mix in order to achieve maximum consolidation.

2. Of the three coarse aggregate factors tested, none appeared to be more influenced toward strength change due to a change in the void content. Each of them had approximately the same relationship between splitting tensile strength and void content.

3. Although not statistically verifiable, of the three coarse aggregate factors tested, the lower the coarse aggregate factor the higher the anticipated splitting tensile strength for a given void content.

4. A given consolidation effort resulted in different levels of consolidation for various coarse aggregate factors.

5. A 0.80 coarse aggregate factor appeared to be the optimum value (within the range tested) for the materials used and the consolidation effort

imparted in this testing program. For concrete made with differing materials, the Fineness Modulus Method of mix design should be employed to determine the coarse aggregate factor to be used.

Coarse Aggregate Size: The following conclusions were based on the results of the literature review and three tests designed to compare the effects of a consolidation effort on concrete containing maximum coarse aggregate sizes of 3/4, 1, and 1-1/2 in. All other mix design and test conditions were held constant between the three tests.

1. The choice of a maximum size coarse aggregate is governed by the width of the section and the spacing of the reinforcement. Consideration should also be given to the desired void content of the hardened concrete when choosing the maximum size of coarse aggregate due to its influence on the resulting void content of a mix.

2. Research indicated that increases in the maximum aggregate size up to 1-1/2 in. tended to increase the strength of the concrete. Beyond 1-1/2 in. this phenomenon no longer applied.

3. Research determined that a maximum aggregate size of 1-1/2 in. was more desirable than 2-1/2 in. in terms of achieved consolidation.

4. This study showed that a change in void content affected the strength of the larger aggregate much more than that of the smaller aggregate.

5. Within the range of achieved void content, the 1-1/2 in. aggregate had the highest strength for a given void content.

6. For the degree of consolidation applied, practically the same void content was realized regardless of the maximum aggregate size.

7. Since 1-1/2 in. aggregate is known to produce concrete with void contents almost equal to the smaller aggregates, is more desirable in terms of

consolidation than larger aggregates, results in higher strengths (for a given void content) than the smaller aggregates tested in this study, and is more economical to produce, it can be concluded that the 1-1/2 in. aggregate is an optimum size for best consolidation results.

<u>Spacing of the Vibrators</u>: The following conclusions were based on the literature review and three tests designed to compare the effects of a consolidation effort on concrete vibrated by paving vibrators spaced at 12, 18, and 24 in. All mix design requirements and other test conditions were held constant between the three tests.

1. The only property of the hardened concrete necessary to determine if a change in vibrator spacing benefits the CRCP is the void content found exactly between the paths of two vibrators.

2. There was little statistical difference between the void content of the concrete consolidated with any of the three vibrator spacings studied, but it could be said that the smaller the spacing the higher the degree of consolidation.

3. Unless there is a long term cost saving associated with reducing the maximum allowable spacing requirement from 24 in., due to a slight reduction in void content, to balance the increased construction costs, the maximum spacing requirement should remain at 24 in.

<u>Method of Mounting the Vibrators</u>: The following conclusions were made based on the literature review and four tests designed to compare the effect of a consolidation effort on concrete vibrated with a paving vibrator that traveled perpendicular to the direction of travel versus that vibrated at three different spacings (12, 18, and 24 in.) where the vibrators traveled parallel to the direction of travel. All of the mix design requirements and other test conditions

were held constant between the four tests.

1. The SDHPT's specifications contain no provisions devoted to the use of a vibrator mounting procedure other than parallel to the direction of travel of the paving machine.

2. Paving vibrators mounted perpendicular to the direction of travel should be mounted so that they are at least end to end, and they should ideally be overlapped almost half the length of the vibrator's head.

3. Requirements on paving train speed must vary between different mounting methods.

4. Proper use of vibrators mounted perpendicular to the direction of travel should eliminate the varying degrees of consolidation across the width of the CRCP found when the vibrators travel parallel to the direction of travel.

5. Problems with this study in reaching the expected relationship between void content and splitting tensile strengths on the test where the vibrator traveled perpendicular to the direction of travel could have been associated with:

a. The inability of the vibrator to liquefy the concrete and consolidate it at the paving speed used.

b. The size and distribution of the voids and their subsequent effect on strength.

c. Problems in the performance of ASTM C642 on determining the void content of the mix, although this was not thought to be the case.

6. The graph of acceleration output vs. time for the test were the vibrator moved perpendicular to the direction of travel revealed that a wave form was never encountered. Therefore, it would be expected that the concrete in this test was not properly consolidated.

7. The concrete consolidated in the laboratory with one vibrator that

moved perpendicular to the direction of travel was of generally poorer quality than that consolidated with the conventional mounting method.

In the field, however, adequate consolidation was observed with the perpendicular mounting. This is attributed to the extra vibrating effort provided by the pan vibrator immediately following the gang mounted spud vibrators.

Superplasticizers with and without Set Retarders: The following conclusions were made based on the literature review and an analysis of the results of the two tests performed during the laboratory investigation.

1. In CRCP construction there is only one possible benefit to be gained by the use of superplasticizing admixtures. They can be used to add to the strength of the concrete at a given void content level.

2. Superplasticizers tend to cause a tremendous increase in the rate of slump loss for low slump the concrete at elevated temperatures, therefore making it very difficult to vibrate and subsequently consolidate.

3. Set retarders tend to diminish the rapid slump loss caused by the superplasticizers, however, they also have a remarkable effect on prolonging the setting time of the concrete.

4. The use of the superplasticizers, both with and without, set retarders had detrimental effects on the consolidation of the simulated CRCP slabs.

Variations in Consolidation with Pavement Depth: The following conclusions were made based on the literature review and an analysis of the results of all 8 tests performed during the laboratory investigation.

1. There has long been concern that the bottom of CRCP slabs is not receiving adequate consolidation when compared to the top of the slabs.

2. The concrete found in the bottom of the simulated CRCP slabs was of significantly higher quality than that found in the top of the slabs. The

evidence found during the laboratory investigation (based on strength, coarse aggregate fracture, and void content) was almost totally conclusive of this finding.

3. The reasons for finding the top to be less consolidated than the bottom may include:

a. The weight of the overburden of concrete may aid in the consolidation of the bottom portion of the CRCP slab.

b. Air moving upward from the bottom of the CRCP slab while the concrete is in the liquid state during vibration may become trapped in the upper portion of the slab when vibration is stopped and the internal friction of the mix restored.

c. The upward forces produced in the concrete above the vibrators may counteract the gravitational forces necessary to adequately consolidate the mix.

d. Dragging the vibrators through the upper portion of the CRCP slab may inherently lead to a higher void content in their paths, particularly if the paving speed is excessive.

4. Consideration should be given to trying to raise the vibrators to a position above the desired level of the concrete in order to maintain all vibratory forces downward on the concrete being consolidated (this conclusion is based on information derived from the results of the study on the acceleration readings).

5. The problems associated with the consolidation of CRCP are probably not due to a lack of consolidation in the bottom of the slabs; at least not when the concrete is vibrated with current slip-form paving vibrators. It can, therefore, be concluded that the concrete is only as good as the top section of the CRCP slab.

Acceleration: The following conclusions were made based on the literature review and an analysis of the acceleration data recorded during the laboratory and field investigations. Due to problems in recording the data, results were not available for all tests; however, general conclusions could still be drawn.

1. Many researchers agree that acceleration is the most significant parameter affecting consolidation during vibration.

2. Acceleration is a function of frequency and amplitude.

3. The accleration of a vibrator can be set to almost any level by varying either the frequency or the amplitude. Since acceleration is most sensitive to changes in frequency, and since most vibrators today allow for changes to be made in their frequency, this is the easiest method of altering the acceleration produced by a vibrator.

4. A plot of acceleration output vs. time revealed that the concrete remained stationary until the vibrator approached. It then had a peak acceleration reading (probably due to the initial slumping of the mix), and finally picked up a wave form that lasted for a few seconds until the internal friction of the mix was restored.

5. The longer the wave form was allowed to extend along the time axis, the more likely it would be that the entrapped air was given enough time to rise to the surface and escape.

6. A review of particle dynamics revealed that, while the linear momentum and the energy imparted on the mix could not be determined per se, a reference for predicting if one test received more momentum or energy of particles could be determined by integrating the acceleration curve with respect to time.

7. A relative energy of no less than approximately 300 ft-lb is necessary to achieve a degree of consolidation (based on AASHTO T121) of greater than or equal to 97 percent.

Recommendations

Based on the results of the literature review, the laboratory investigation and analysis, and a limited field study, the following recommendations for improving the consolidation of CRCP can be made:

1. Specify a maximum allowable coarse aggregate factor of 0.80 and recommend that this coarse aggregate factor be used (if the gradation of aggregates used is similar to those used in this test). If materials with different gradations are used, then the Fineness Modulus Method of mix design should be used to determine a coarse aggregate factor.

2. Specify a maximum allowable coarse aggregate size of 1-1/2 in. and recommend that this coarse aggregate size be used.

3. Specify a maximum allowable vibrator spacing of 24 in. for paving trains with vibrators mounted parallel to the direction of travel.

4. Provide for careful monitoring of the concrete consolidation when the slump of the fresh concrete is less the 1-1/2 inch and the spud vibrators are mounted perpendicular to the direction of travel of the paving machine.

5. Do not allow superplasticizing admixtures to be used until further research can be conducted to determine procedures and guidelines whereby they can be used effectively.

6. Monitor the consolidation being obtained in the top portion of the CRCP slab (perhaps by the use of a nuclear density gage) since this will be the part of the slab with the highest void content, provided no surface vibration is administered.

7. Evaluate the Vibrator Monitoring System (VMS) on one or more field projects.

8. Specify a relative vibrator energy input of no less than 300 ft-lb into

the fresh concrete or a dry unit weight of no less than 97 percent of the maximum field unit weight (AASHTO T121).

Recommended Areas for Future Research

The following list of possible research topics was developed during the course of performing this study. Each of the items suggest possible areas where further research needs to be conducted to aid in the study of consolidation in general and as it applies to CRCP construction.

1. A simple test procedure needs to be designed to determine the void content of concrete with visible honeycombing. ASTM C642 is not sufficient when the voids are too large for the surface tension of the water to retain itself in the specimen during the SSD weight readings. Other possible test methods were presented in this study (see Appendix F), but they are either error prone or cumbersome and extremely time consuming.

2. Extended research is necessary in the area of accelerations produced in a concrete mix during vibration. Most research that has been performed dealing with this topic has been limited to small quantities of concrete, with problems induced due to the shape and size of the forms. As determined in this study, accelerations can be monitored and can present some very interesting information. Future research needs to be conducted in situations that simulate field conditions so that all influences inherent to the testing procedure are eliminated.

3. A culmination of research already conducted needs to be performed in order to determine if CRCP in general has been found to lack consolidation in the bottom of the slab. The concern that the concrete in the bottom of the CRCP slab is less consolidated than the top needs to be either confirmed or refuted. This concern could be based on concrete examined at failure areas, especially near construction joints where it has been proven that the concrete will lack consolidation in the bottom. This study presents reasons why concrete

near a construction joint does not receive adequate consolidation, especially in the bottom of the slab. There is enough research on record, that includes core analysis results, to draw a well substantiated conclusion to this problem.

4. Further research needs to be conducted to determine exactly what is occurring when vibrators are moved through a pavement perpendicular to the direction of travel. The single test in this study was simply not enough to produce any conclusive results. A comprehensive study of this topic needs to be performed in order to consider all of the aspects surrounding its implication. A recommended paving speed needs to be determined for its use. It would be assumed, from the findings of this study, that the paving speed would be greatly reduced from that of the conventional method. Also, the spacing requirements of vibrators mounted in this fashion need to be determined.

5. Research should be conducted to determine if raising the vibrators above mid-depth will result in better consolidation in the top of the slab, and if this will affect the consolidation achieved in the bottom of the slab. Perhaps moving the vibrators above the intended depth of the slab will allow the top portion of the slab to receive better consolidation with very little loss in consolidation in the bottom.

6. Research needs to be conducted in developing superplasticing admixtures that can be used effectively when low slump concrete is being placed. The benefits that they can provide in the areas of strength are such that this problem is of immediate concern. The problem of the rapid slump loss needs to be eliminated, and the use of set retarders may not be the answer.

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APPENDIX A

AGGREGATE TEST RESULTS

Coarse aggregate information.

Item	Value
Rodded Dry Unit Weight	102.6 pcf
Rodded SSD Unit Weight	83.3 pcf
Shoveled SSD Unit Weight	78.2 pcf
Bulk Specific Gravity	2.74
Bulk Specific Gravity (SSD)	2.79
Apparent Specific Gravity	2.85
Absorption Percentage	1.30 %

Seive analysis:

Seive Size	Cumulative % Retained
1 in.	14.2
3/4 in.	44.2
1/2 in.	74.4
3/8 in.	89.9
# 4	99.7
Pan	100.0

Fine aggregate information.

Item	Value
Rodded SSD Unit Weight	101.6 pcf
Shoveled SSD Unit Weight	N/A
Bulk Specific Gravity	2.59
Bulk Specific Gravity (SSD)	2.63
Apparent Specific Gravity	2.71
Absorption Percentage	1.70 %

Seive analysis:

Seive Size	Cumulative % Retained
# 4	0.18
# 8	8.3
# 16	21.0
# 30	37.6
# 50	81.5
# 100	98.6
# 200	99.9
Pan	100.0

APPENDIX B

PRELIMINARY MIX DESIGNS

Batch Design 1.

Fine Aggregate Moisture Content .... +0.59 %
Coarse Aggregate Moisture Content .... -0.85 %

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.15	3.15	28.70		28.70		28.70	28.70	0.15	9.90
Water	12.39	0.19	1.00	11.60	+0.72	12.32	-0.02	12.30	11.58	0.19	12.58
F.A.	24.14	0.36	2.59	58.52	+0.35	58.87	+0.03	58.90	58.55	0.36	24.56
C.A.	48.73	0.73	2.74	124.98	-1.06	123.92	-0.02	123.90	124.96	0.73	49.55
Air	5.00	0.08								0.08	3.40
Totals	100.00	1.50		223.80		223.80		223.79	223.79	1.47	100.00

Actual Air Content .... 3.40 %
Slump .... 1-1/4 in.
Actual Coarse Aggregate Factor 0.81
Air Entrainment .... 18 mL

Calculated Unit Weight ..... 151.73 pcf
Measured Unit Weight ...... 154.12 pcf

Note: This concrete was batched with a 1-1/2 in. maximum size aggregate, and it was used in Tests 1, 2, 3, and 4.

Batch Design 2.

Fine Aggregate Moisture Content .... +3.58 %
Coarse Aggregate Moisture Content .... -0.72 %

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.15	3.15	28.70		28.70		28.70	28.70	0.15	9.89
Water	12.29	0.18	1.00	11.50	-0.88	10.62	-0.02	10.60	11.48	0.18	12.46
F.A.	21.20	0.32	2.59	51.40	+1.84	53.24	-0.04	53.20	51.36	0.32	21.53
C.A.	51.78	0.78	2.74	132.79	-0.96	131.84	-0.04	131.80	132.75	0.78	52.61
Air	5.00	0.08								0.08	3.50
Totals	100.00	1.50		224.39		224.39		224.29	224.29	1.48	100.00

Actual Air Content .... 3.50 %
Slump .... 1-1/2 in.
Actual Coarse Aggregate Factor 0.86
Air Entrainment .... 18 mL

Calculated Unit Weight ..... 151.97 pcf
Measured Unit Weight ...... 155.72 pcf

Note: This concrete was batched with a 1-1/2 in. maximum size aggregate, and it was used in Test 6.

Batch Design 3.

Fine Aggregate Moisture Content .... +5.46 %
Coarse Aggregate Moisture Content .... −0.76 %

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.15	3.15	28.70		28.70		28.70	28.70	0.15	9.82
Water	12.61	0.19	1.00	11.80	−2.59	9.21	−0.31	8.90	11.49	0.18	12.39
F.A.	26.36	0.40	2.59	63.91	+3.49	67.40	+0.00	67.40	63.91	0.40	26.60
C.A.	46.30	0.69	2.74	118.73	−0.90	117.83	−0.03	117.80	118.70	0.69	46.70
Air	5.00	0.08								0.08	4.50
Totals	100.00	1.50		223.14		223.14		222.80	222.80	1.49	100.00

Actual Air Content .... 4.50 %
Slump .... 1-1/4 in.
Actual Coarse Aggregate Factor 0.76
Air Entrainment .... 18 mL

Calculated Unit Weight ..... 149.86 pcf
Measured Unit Weight ...... 154.12 pcf

Note: This concrete was batched with a 1-1/2 in. maximum aggregate size, and it was used in Test 5.

Batch Design 4.

Fine Aggregate Moisture Content .... +1.90 %
Coarse Aggregate Moisture Content .... -0.88 %

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.15	3.15	28.70		28.70		28.70	28.70	0.15	9.90
Water	12.61	0.19	1.00	11.80	-0.17	11.63	-0.23	11.40	11.57	0.19	12.45
F.A.	26.36	0.40	2.59	63.91	+1.21	65.12	-0.02	65.10	63.89	0.40	26.54
C.A.	46.30	0.69	2.74	118.73	-1.04	117.69	+0.01	117.70	118.74	0.69	46.62
Air	5.00	0.08								0.08	4.60
Totals	100.00	1.50		223.14		223.14		222.90	222.90	1.49	100.00

Actual Air Content .... 4.60 %
Slump .... 1-1/4 in.
Actual Coarse Aggregate Factor 0.77
Air Entrainment .... 18 mL

Calculated Unit Weight ..... 149.62 pcf
Measured Unit Weight ...... 153.72 pcf

<u>Note</u>: This concrete was batched with a 1 in. maximum aggregate size, and it was used in Test 7.

Batch Design 5.

Fine Aggregate Moisture Content .... +2.64 %
Coarse Aggregate Moisture Content .... -0.64 %

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.15	3.15	28.70		28.70		28.70	28.70	0.15	9.90
Water	12.61	0.19	1.00	11.80	-0.93	10.87	+0.03	10.90	11.83	0.19	12.63
F.A.	26.36	0.40	2.59	63.91	+1.69	65.60	+0.00	65.60	63.91	0.40	26.35
C.A.	46.30	0.69	2.74	118.73	-0.76	117.97	+0.03	118.00	118.76	0.69	46.29
Air	5.00	0.08								0.08	5.00
Totals	100.00	1.50		223.14		223.14		223.20	223.20	1.50	100.00

Actual Air Content .... 5.00 %
Slump .... 1-1/2 in.
Actual Coarse Aggregate Factor 0.76
Air Entrainment .... 18 ml.

Calculated Unit Weight ..... 148.73 pcf
Measured Unit Weight ...... 152.12 pcf

Note: This concrete was batched with a 3/4 in. maximum aggregate size, and it was used in Test 8.

Batch Design 6.

Fine Aggregate Moisture Content .... +1.88 %
Coarse Aggregate Moisture Content .... -0.81 %

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.15	3.15	28.70		28.70		28.70	28.70	0.15	9.86
Water	10.53	0.16	1.00	9.86	-0.17	9.69	+0.01	9.70	9.87	0.16	10.68
F.A.	26.00	0.39	2.59	63.03	+1.18	64.21	-0.01	64.20	63.02	0.39	26.32
C.A.	48.73	0.73	2.74	124.98	-1.01	123.97	+0.03	124.00	125.01	0.73	49.35
Air	5.00	0.08								0.08	3.80
Totals	100.00	1.50		226.57		226.57		226.60	226.60	1.48	100.00

Actual Air Content .... 3.80 %
Slump .... 1 in.
Actual Coarse Aggregate Factor 0.81
Air Entrainment .... 18 ml.
Superplasticizing Agent .... 100 ml.

Calculated Unit Weight ..... 152.95 pcf
Measured Unit Weight ...... 156.92 pcf

Note: This concrete was batched with a 1-1/2 in. maximum aggregate size, and it was used in Tests 9, 10, and 11. Test 11 used a superplasticizing agent with a set retarder included; the amount of the agent remained the same.

APPENDIX C

ACTUAL MIX DESIGNS

Test 1, Batch 1.

Date	04/16/83
Mix Design Number	1
F.A. Moisture Content	+1.20 %
C.A. Moisture Content	-1.03 %
Air Entraining Agent	66 mL
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values	
Cem. Factor	5.56 sk/cy
Air Content	4.00 %
C.A. Factor	0.81
W/C Ratio	0.40
Slump	1 in.
Calc. Unit Weight	150.77 pcf
Meas. Unit Weight	156.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.83
Water	12.39	0.68	1.00	42.53	+2.15	44.68	+0.02	44.70	42.55	0.68	12.53
F.A.	24.14	1.33	2.59	214.58	+2.57	217.15	+0.05	217.20	214.63	1.33	24.40
C.A.	48.73	2.68	2.74	458.26	-4.72	453.54	-0.40	453.50	458.22	2.68	49.24
Air	5.00	0.28								0.22	4.00
Totals	100.00	5.50		820.61		820.61		820.60	820.60	5.44	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 1, Batch 2.

Date	04/16/83
Mix Design Number	1
F.A. Moisture Content	+1.20 %
C.A. Moisture Content	-1.03 %
Air Entraining Agent	66 ml.
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values

Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values

Cem. Factor	5.55 sk/cy
Air Content	4.40 %
C.A. Factor	0.81
W/C Ratio	0.39
Slump	1 in.
Calc. Unit Weight	150.50 pcf
Meas. Unit Weight	154.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.83
Water	12.39	0.68	1.00	42.53	+2.15	44.68	-1.28	43.40	41.25	0.66	12.14
F.A.	24.14	1.33	2.59	214.58	+2.57	217.15	+0.05	217.20	214.63	1.33	24.39
C.A.	48.73	2.68	2.74	458.26	-4.72	453.54	-0.40	453.50	458.22	2.68	49.23
Air	5.00	0.28								0.24	4.40
Totals	100.00	5.50		820.61		820.61		819.30	819.30	5.44	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 1, Batch 3.

Date	04/16/83
Mix Design Number	1
F.A. Moisture Content	+1.20 %
C.A. Moisture Content	-1.03 %
Air Entraining Agent	66 ml.
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values	
Cem. Factor	5.57 sk/cy
Air Content	4.20 %
C.A. Factor	0.81
W/C Ratio	0.39
Slump	1 in.
Calc. Unit Weight	150.87 pcf
Meas. Unit Weight	156.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.86
Water	12.39	0.68	1.00	42.53	+2.15	44.68	-1.48	43.20	41.05	0.66	12.12
F.A.	24.14	1.33	2.59	214.58	+2.57	217.15	+0.05	217.20	214.63	1.33	24.46
C.A.	48.73	2.68	2.74	458.26	-4.72	453.54	-0.40	453.50	458.22	2.68	49.36
Air	5.00	0.28								0.23	4.20
Totals	100.00	5.50		820.61		820.61		819.10	819.10	5.43	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 1, Batch 4.

Date	04/16/83
Mix Design Number	1
F.A. Moisture Content	+1.20 %
C.A. Moisture Content	-1.03 %
Air Entraining Agent	66 mL
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values	
Cem. Factor	5.56 sk/cy
Air Content	4.30 %
C.A. Factor	0.81
W/C Ratio	0.39
Slump	1 in.
Calc. Unit Weight . .	150.66 pcf
Meas. Unit Weight . .	154.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.84
Water	12.39	0.68	1.00	42.53	+2.15	44.68	-1.28	43.40	41.25	0.66	12.16
F.A.	24.14	1.33	2.59	214.58	+2.57	217.15	+0.05	217.20	214.63	1.33	24.42
C.A.	48.73	2.68	2.74	458.26	-4.72	453.54	-0.40	453.50	458.22	2.68	49.28
Air	5.00	0.28								0.23	4.30
Totals	100.00	5.50		820.61		820.61		819.30	819.30	5.44	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 2, Batch 1.

		Design Values		Actual Values	
Date	04/23/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.51 sk/cy
Mix Design Number	1	Air Content	5.00 %	Air Content	4.80 %
F.A. Moisture Content	+1.54 %	C.A. Factor	0.80	C.A. Factor	0.80
C.A. Moisture Content	-1.05 %	W/C Ratio	0.40	W/C Ratio	0.40
Air Entraining Agent	66 mL	Slump	1-1/2 in.	Slump	1-3/4 in.
Air Temperature	75°F	Unit Weight	149.20 pcf	Calc. Unit Weight	149.53 pcf
Max. C.A. Size	1-1/2 in.			Meas. Unit Weight	154.92 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.75
Water	12.39	0.68	1.00	42.53	+1.51	44.04	-0.04	44.00	42.49	0.68	12.41
F.A.	24.14	1.33	2.59	214.58	+3.30	217.88	+0.02	217.90	214.60	1.33	24.19
C.A.	48.73	2.68	2.74	458.26	-4.81	453.45	+0.05	453.50	458.31	2.68	48.84
Air	5.00	0.28								0.26	4.80
Totals	100.00	5.50		820.61		820.61		820.60	820.60	5.49	100.00

Note: Vibrators spaced at 24 in. and moved parallel to the direction of travel.

Test 2, Batch 2.

		Design Values		Actual Values	
Date	04/23/83				
Mix Design Number	1	Cem. Factor	5.50 sk/cy	Cem. Factor	5.53 sk/cy
F.A. Moisture Content	+1.54 %	Air Content	5.00 %	Air Content	4.50 %
C.A. Moisture Content	-1.05 %	C.A. Factor	0.80	C.A. Factor	0.80
Air Entraining Agent	66 ml.	W/C Ratio	0.40	W/C Ratio	0.40
Air Temperature	75°F	Slump	1-1/2 in.	Slump	1 in.,
Max. C.A. Size	1-1/2 in.	Unit Weight	149.20 pcf	Calc. Unit Weight	150.00 pcf
				Meas. Unit Weight	154.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.78
Water	12.39	0.68	1.00	42.53	+1.51	44.04	-0.04	44.00	42.49	0.68	12.45
F.A.	24.14	1.33	2.59	214.58	+3.30	217.88	+0.02	217.90	214.60	1.33	24.27
C.A.	48.73	2.68	2.74	458.26	-4.81	453.45	+0.05	453.50	458.31	2.68	49.00
Air	5.00	0.28								0.25	4.50
Totals	100.00	5.50		820.61		820.61		820.60	820.60	5.47	100.00

Note: Vibrators spaced at 24 in. and moved parallel to the direction of travel.

Test 2, Batch 3.

		Design Values		Actual Values	
Date	04/23/83				
Mix Design Number	1				
F.A. Moisture Content	+1.54 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.53 sk/cy
C.A. Moisture Content	-1.05 %	Air Content	5.00 %	Air Content	4.10 %
Air Entraining Agent	66 ml.	C.A. Factor	0.80	C.A. Factor	0.80
Air Temperature	75°F	W/C Ratio	0.40	W/C Ratio	0.41
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/2 in.
		Unit Weight	149.20 pcf	Calc. Unit Weight	150.53 pcf
				Meas. Unit Weight	155.72 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.75
Water	12.39	0.68	1.00	42.53	+1.51	44.04	+0.96	45.00	43.49	0.70	12.75
F.A.	24.14	1.33	2.59	214.58	+3.30	217.88	+0.02	217.90	214.60	1.33	24.30
C.A.	48.73	2.68	2.74	458.26	-4.81	453.45	+0.05	453.50	458.31	2.68	49.05
Air	5.00	0.28								0.22	4.10
Totals	100.00	5.50		820.61		820.61		821.60	821.60	5.46	100.00

Note: Vibrators spaced at 24 in. and moved parallel to the direction of travel.

Test 2, Batch 4.

Date	04/23/83
Mix Design Number	1
F.A. Moisture Content	+1.54 %
C.A. Moisture Content	-1.05 %
Air Entraining Agent	66 ml.
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values

Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values

Cem. Factor	5.53 sk/cy
Air Content	4.50 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Calc. Unit Weight	150.00 pcf
Meas. Unit Weight	154.52 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.75
Water	12.39	0.68	1.00	42.53	+1.51	44.04	-0.04	44.00	42.49	0.68	12.45
F.A.	24.14	1.33	2.59	214.58	+3.30	217.88	+0.02	217.90	214.60	1.33	24.27
C.A.	48.73	2.68	2.74	458.26	-4.81	453.45	+0.05	453.50	458.31	2.68	49.00
Air	5.00	0.28								0.25	4.50
Totals	100.00	5.50		820.61		820.61		820.60	820.60	5.47	100.00

Note: Vibrators spaced at 24 in. and moved parallel to the direction of travel.

Test 3, Batch 1.

		Design Values		Actual Values	
Date	04/29/83				
Mix Design Number	1				
F.A. Moisture Content	+1.42 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.53 sk/cy
C.A. Moisture Content	-1.04 %	Air Content	5.00 %	Air Content	4.80 %
Air Entraining Agent	66 ml.	C.A. Factor	0.80	C.A. Factor	0.80
Air Temperature	75°F	W/C Ratio	0.40	W/C Ratio	0.40
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	2 in.
		Unit Weight	149.20 pcf	Calc. Unit Weight	149.78 pcf
				Meas. Unit Weight	153.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.78
Water	12.39	0.68	1.00	42.53	+1.72	44.25	-0.95	43.30	41.58	0.67	12.18
F.A.	24.14	1.33	2.59	214.58	+3.05	217.62	-0.02	217.60	214.56	1.33	24.26
C.A.	48.73	2.68	2.74	458.26	-4.77	453.49	+0.01	453.50	458.27	2.68	48.98
Air	5.00	0.28								0.26	4.80
Totals	100.00	5.50		820.61		820.61		819.61	819.61	5.47	100.00

Note: Vibrators spaced at 12 in. and moved parallel to the direction of travel.

Test 3, Batch 2.

Date	04/29/83
Mix Design Number	1
F.A. Moisture Content	+1.42 %
C.A. Moisture Content	-1.04 %
Air Entraining Agent	66 ml.
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values	
Cem. Factor	5.57 sk/cy
Air Content	4.50 %
C.A. Factor	0.81
W/C Ratio	0.38
Slump	1-3/4 in.
Calc. Unit Weight . .	150.70 pcf
Meas. Unit Weight . .	153.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.86
Water	12.39	0.68	1.00	42.53	+1.72	44.25	-2.55	41.70	39.98	0.64	11.80
F.A.	24.14	1.33	2.59	214.58	+3.05	217.62	-0.02	217.60	214.56	1.33	24.46
C.A.	48.73	2.68	2.74	458.26	-4.77	453.49	+0.01	453.50	458.27	2.68	49.38
Air	5.00	0.28								0.24	4.50
Totals	100.00	5.50		820.61		820.61		818.01	818.01	5.43	100.00

Note: Vibrators spaced at 12 in. and moved parallel to the direction of travel.

Test 3, Batch 3.

Date	04/29/83
Mix Design Number	1
F.A. Moisture Content	+1.42 %
C.A. Moisture Content	-1.04 %
Air Entraining Agent	66 ml.
Air Temperature	75°F
Max. C.A. Size	1-1/2 in.

Design Values

Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values

Cem. Factor	5.58 sk/cy
Air Content	4.60 %
C.A. Factor	0.81
W/C Ratio	0.37
Slump	1-1/4 in.
Calc. Unit Weight	150.79 pcf
Meas. Unit Weight	153.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.88
Water	12.39	0.68	1.00	42.53	+1.72	44.25	-3.45	40.80	39.08	0.63	11.56
F.A.	24.14	1.33	2.59	214.58	+3.05	217.62	-0.02	217.60	214.56	1.33	24.50
C.A.	48.73	2.68	2.74	458.26	-4.77	453.49	+0.01	453.50	458.27	2.68	49.46
Air	5.00	0.28								0.25	4.60
Totals	100.00	5.50		820.61		820.61		817.11	817.11	5.42	100.00

Note: Vibrators spaced at 12 in. and moved parallel to the direction of travel.

Test 3, Batch 4.

		Design Values		Actual Values	
Date	04/29/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.61 sk/cy
Mix Design Number	1	Air Content	5.00 %	Air Content	4.30 %
F.A. Moisture Content	+1.42 %	C.A. Factor	0.80	C.A. Factor	0.82
C.A. Moisture Content	-1.04 %	W/C Ratio	0.40	W/C Ratio	0.37
Air Entraining Agent	66 ml.	Slump	1-1/2 in.	Slump	1 in.
Air Temperature	75°F	Unit Weight	149.20 pcf	Calc. Unit Weight ..	151.41 pcf
Max. C.A. Size	1-1/2 in.			Meas. Unit Weight ..	154.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.78
Water	12.39	0.68	1.00	42.53	+1.72	44.25	-3.95	40.30	38.58	0.62	11.46
F.A.	24.14	1.33	2.59	214.58	+3.05	217.62	-0.02	217.60	214.56	1.33	24.61
C.A.	48.73	2.68	2.74	458.26	-4.77	453.49	+0.01	453.50	458.27	2.68	49.70
Air	5.00	0.28								0.23	4.30
Totals	100.00	5.50		820.61		820.61		816.61	816.61	5.39	100.00

Note: Vibrators spaced at 12 in. and moved parallel to the direction of travel.

Test 4, Batch 1.

Date	07/09/83	Design Values		Actual Values	
Mix Design Number	1				
F.A. Moisture Content	+2.67 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.56 sk/cy
C.A. Moisture Content	-1.17 %	Air Content	5.00 %	Air Content	4.00 %
Air Entraining Agent	66 ml.	C.A. Factor	0.80	C.A. Factor	0.81
Air Temperature	88°F	W/C Ratio	0.40	W/C Ratio	0.40
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/4 in.
		Unit Weight	149.20 pcf	Calc. Unit Weight	150.76 pcf
				Meas. Unit Weight	156.51 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.83
Water	12.39	0.68	1.00	42.53	-0.37	42.17	+0.03	42.20	42.56	0.68	12.53
F.A.	24.14	1.33	2.59	214.58	+5.73	220.31	-0.01	220.30	214.57	1.33	24.39
C.A.	48.73	2.68	2.74	458.26	-5.36	452.90	+0.00	452.90	458.26	2.68	49.24
Air	5.00	0.28								0.22	4.00
Totals	100.00	5.50		820.61		820.61		820.59	820.59	5.44	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 4, Batch 2.

Date	07/09/83
Mix Design Number	1
F.A. Moisture Content	+2.67 %
C.A. Moisture Content	-1.17 %
Air Entraining Agent	66 ml.
Air Temperature	88°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values	
Cem. Factor	5.54 sk/cy
Air Content	4.20 %
C.A. Factor	0.81
W/C Ratio	0.40
Slump	1-1/2 in.
Calc. Unit Weight . .	150.45 pcf
Meas. Unit Weight . .	154.35 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.81
Water	12.39	0.68	1.00	42.53	-0.37	42.17	+0.03	42.20	42.56	0.68	12.51
F.A.	24.14	1.33	2.59	214.58	+5.73	220.31	-0.01	220.30	214.57	1.33	24.34
C.A.	48.73	2.68	2.74	458.26	-5.36	452.90	+0.00	452.90	458.26	2.68	49.14
Air	5.00	0.28								0.23	4.20
Totals	100.00	5.50		820.61		820.61		820.59	820.59	5.45	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 4, Batch 3.

		Design Values		Actual Values	
Date	07/09/83				
Mix Design Number	1	Cem. Factor	5.50 sk/cy	Cem. Factor	5.57 sk/cy
F.A. Moisture Content	+2.67 %	Air Content	5.00 %	Air Content	3.80 %
C.A. Moisture Content	-1.17 %	C.A. Factor	0.80	C.A. Factor	0.81
Air Entraining Agent	66 ml.	W/C Ratio	0.40	W/C Ratio	0.40
Air Temperature	88°F	Slump	1-1/2 in.	Slump	2 in.
Max. C.A. Size	1-1/2 in.	Unit Weight	149.20 pcf	Calc. Unit Weight	151.08 pcf
				Meas. Unit Weight	154.13 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.85
Water	12.39	0.68	1.00	42.53	-0.37	42.17	+0.03	42.20	42.56	0.68	12.56
F.A.	24.14	1.33	2.59	214.58	+5.73	220.31	-0.01	220.30	214.57	1.33	24.44
C.A.	48.73	2.68	2.74	458.26	-5.36	452.90	+0.00	452.90	458.26	2.68	49.35
Air	5.00	0.28								0.21	3.80
Totals	100.00	5.50		820.61		820.61		820.59	820.59	5.43	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 4, Batch 4.

Date	07/09/83
Mix Design Number	1
F.A. Moisture Content	+2.67 %
C.A. Moisture Content	-1.17 %
Air Entraining Agent	66 mL
Air Temperature	88°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.20 pcf

Actual Values	
Cem. Factor	5.57 sk/cy
Air Content	3.80 %
C.A. Factor	0.81
W/C Ratio	0.40
Slump	1-1/2 in.
Calc. Unit Weight	151.08 pcf
Meas. Unit Weight	154.35 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.85
Water	12.39	0.68	1.00	42.53	-0.37	42.17	+0.03	42.20	42.56	0.68	12.56
F.A.	24.14	1.33	2.59	214.58	+5.73	220.31	-0.01	220.30	214.57	1.33	24.44
C.A.	48.73	2.68	2.74	458.26	-5.36	452.90	+0.00	452.90	458.26	2.68	49.35
Air	5.00	0.28								0.21	3.80
Totals	100.00	5.50		820.61		820.61		820.59	820.59	5.43	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 5, Batch 1.

Date	05/19/83
Mix Design Number	3
F.A. Moisture Content	+3.66 %
C.A. Moisture Content	-0.66 %
Air Entraining Agent	66 mL
Air Temperature	76°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	1-1/2 in.
Unit Weight	148.76 pcf

Actual Values	
Cem. Factor	5.55 sk/cy
Air Content	5.50 %
C.A. Factor	0.77
W/C Ratio	0.36
Slump	6-1/2 in.
Calc. Unit Weight	149.35 pcf
Meas. Unit Weight	149.42 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.83
Water	12.61	0.69	1.00	43.27	-5.70	37.56	-4.96	32.60	38.31	0.61	11.27
F.A.	26.36	1.45	2.59	234.34	+8.58	242.91	-0.01	242.90	234.33	1.45	26.63
C.A.	46.30	2.55	2.74	435.35	-2.87	432.47	+0.03	432.50	435.38	2.55	46.77
Air	5.00	0.28								0.30	5.50
Totals	100.00	5.50		818.19		818.19		813.21	813.21	5.44	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 5, Batch 2.

		Design Values		Actual Values	
Date	05/19/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.68 sk/cy
Mix Design Number	3	Air Content	5.00 %	Air Content	4.80 %
F.A. Moisture Content	+3.66 %	C.A. Factor	0.76	C.A. Factor	0.78
C.A. Moisture Content	−0.66 %	W/C Ratio	0.41	W/C Ratio	0.32
Air Entraining Agent	66 ml.	Slump	1-1/2 in.	Slump	1-3/4 in.
Air Temperature	76°F	Unit Weight	148.76 pcf	Calc. Unit Weight	151.79 pcf
Max. C.A. Size	1-1/2 in.			Meas. Unit Weight	151.01 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	−0.04	105.20	105.20	0.54	10.05
Water	12.61	0.69	1.00	43.27	−5.70	37.56	−9.58	27.98	33.69	0.54	10.13
F.A.	26.36	1.45	2.59	234.34	+8.58	242.91	−0.01	242.90	234.33	1.45	27.22
C.A.	46.30	2.55	2.74	435.35	−2.87	432.47	+0.03	432.50	435.38	2.55	47.80
Air	5.00	0.28								0.26	4.80
Totals	100.00	5.50		818.19		818.19		808.59	808.59	5.33	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 5, Batch 3.

		Design Values		Actual Values	
Date	05/19/83				
Mix Design Number	3				
F.A. Moisture Content	+3.66 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.66 sk/cy
C.A. Moisture Content	-0.66 %	Air Content	5.00 %	Air Content	4.20 %
Air Entraining Agent	66 ml.	C.A. Factor	0.76	C.A. Factor	0.78
Air Temperature	76°F	W/C Ratio	0.41	W/C Ratio	0.35
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/4 in.
		Unit Weight	148.76 pcf	Calc. Unit Weight	151.95 pcf
				Meas. Unit Weight	151.54 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	10.02
Water	12.61	0.69	1.00	43.27	-5.70	37.56	-6.86	30.70	36.41	0.58	10.93
F.A.	26.36	1.45	2.59	234.34	+8.58	242.91	-0.01	242.90	234.33	1.45	27.16
C.A.	46.30	2.55	2.74	435.35	-2.87	432.47	+0.03	432.50	435.38	2.55	47.69
Air	5.00	0.28								0.22	4.20
Totals	100.00	5.50		818.19		818.19		811.31	811.31	5.34	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 5, Batch 4.

Date	05/19/83
Mix Design Number	3
F.A. Moisture Content	+3.66 %
C.A. Moisture Content	-0.66 %
Air Entraining Agent	66 ml.
Air Temperature	76°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	1-1/2 in.
Unit Weight	148.76 pcf

Actual Values	
Cem. Factor	5.61 sk/cy
Air Content	4.00 %
C.A. Factor	0.78
W/C Ratio	0.38
Slump	1 in.
Calc. Unit Weight	151.27 pcf
Meas. Unit Weight	153.16 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.94
Water	12.61	0.69	1.00	43.27	-5.70	37.56	-3.36	34.20	39.91	0.64	11.87
F.A.	26.36	1.45	2.59	234.34	+8.58	242.91	-0.01	242.90	234.33	1.45	26.92
C.A.	46.30	2.55	2.74	435.35	-2.87	432.47	+0.03	432.50	435.38	2.55	47.27
Air	5.00	0.28								0.22	4.00
Totals	100.00	5.50		818.19		818.19		814.81	814.81	5.39	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 6, Batch 1.

Date	05/23/83	**Design Values**		**Actual Values**	
Mix Design Number	2	Cem. Factor	5.50 sk/cy	Cem. Factor	5.59 sk/cy
F.A. Moisture Content	+5.60 %	Air Content	5.00 %	Air Content	3.40 %
C.A. Moisture Content	-0.79 %	C.A. Factor	0.85	C.A. Factor	0.86
Air Entraining Agent	66 mL	W/C Ratio	0.40	W/C Ratio	0.40
Air Temperature	80°F	Slump	1-1/2 in.	Slump	1 in.
Max. C.A. Size	1-1/2 in.	Unit Weight	149.59 pcf	Calc. Unit Weight	152.10 pcf
				Meas. Unit Weight	155.94 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.89
Water	12.29	0.68	1.00	42.17	-6.71	35.46	+0.04	35.50	42.21	0.68	12.50
F.A.	21.20	1.17	2.59	188.45	+10.55	199.01	-0.01	199.00	188.44	1.17	21.55
Air	5.00	0.28								0.18	3.40
Totals	100.00	5.50		822.76		822.76		822.80	822.80	5.41	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 6, Batch 2.

Date	05/23/83
Mix Design Number	2
F.A. Moisture Content	+5.60 %
C.A. Moisture Content	-0.79 %
Air Entraining Agent	66 ml.
Air Temperature	80°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.85
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.59 pcf

Actual Values	
Cem. Factor	5.57 sk/cy
Air Content	3.80 %
C.A. Factor	0.86
W/C Ratio	0.40
Slump	3 in.
Calc. Unit Weight	151.47 pcf
Meas. Unit Weight	152.94 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.85
Water	12.29	0.68	1.00	42.17	-6.71	35.46	+0.04	35.50	42.21	0.68	12.45
F.A.	21.20	1.17	2.59	188.45	+10.55	199.01	-0.01	199.00	188.44	1.17	21.46
C.A.	51.78	2.85	2.74	486.90	-3.85	483.05	+0.05	483.10	486.95	2.85	52.43
Air	5.00	0.28								0.21	3.80
Totals	100.00	5.50		822.76		822.76		822.80	822.80	5.43	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 6, Batch 3.

		Design Values		Actual Values	
Date	05/23/83				
Mix Design Number	2				
F.A. Moisture Content	+5.60 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.62 sk/cy
C.A. Moisture Content	-0.79 %	Air Content	5.00 %	Air Content	2.80 %
Air Entraining Agent	66 mL	C.A. Factor	0.85	C.A. Factor	0.87
Air Temperature	80°F	W/C Ratio	0.40	W/C Ratio	0.40
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/4 in.
		Unit Weight	149.59 pcf	Calc. Unit Weight	153.05 pcf
				Meas. Unit Weight	155.14 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.96
Water	12.29	0.68	1.00	42.17	-6.71	35.46	+0.04	35.50	42.21	0.68	12.58
F.A.	21.20	1.17	2.59	188.45	+10.55	199.01	-0.01	199.00	188.44	1.17	21.69
C.A.	51.78	2.85	2.74	486.90	-3.85	483.05	+0.05	483.10	486.95	2.85	52.98
Air	5.00	0.28								0.15	2.80
Totals	100.00	5.50		822.76		822.76		822.80	822.80	5.38	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 6, Batch 4.

Date	05/23/83
Mix Design Number	2
F.A. Moisture Content	+5.60 %
C.A. Moisture Content	-0.79 %
Air Entraining Agent	66 mL
Air Temperature	80°F
Max. C.A. Size	1-1/2 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.85
W/C Ratio	0.40
Slump	1-1/2 in.
Unit Weight	149.59 pcf

Actual Values	
Cem. Factor	5.60 sk/cy
Air Content	3.20 %
C.A. Factor	0.87
W/C Ratio	0.40
Slump	1-1/4 in.
Calc. Unit Weight	152.42 pcf
Meas. Unit Weight	156.90 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.91
Water	12.29	0.68	1.00	42.17	-6.71	35.46	+0.04	35.50	42.21	0.68	12.53
F.A.	21.20	1.17	2.59	188.45	+10.55	199.01	-0.01	199.00	188.44	1.17	21.60
C.A.	51.78	2.85	2.74	486.90	-3.85	483.05	+0.05	483.10	486.95	2.85	52.76
Air	5.00	0.28								0.17	3.20
Totals	100.00	5.50		822.76		822.76		822.80	822.80	5.40	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 7, Batch 1.

		Design Values		Actual Values	
Date	06/02/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.59 sk/cy
Mix Design Number	4	Air Content	5.00 %	Air Content	4.60 %
F.A. Moisture Content	+2.65 %	C.A. Factor	0.76	C.A. Factor	0.77
C.A. Moisture Content	-0.73 %	W/C Ratio	0.41	W/C Ratio	0.37
Air Entraining Agent	66 ml.	Slump	1-1/2 in.	Slump	2 in.
Air Temperature	87°F	Unit Weight	148.76 pcf	Calc. Unit Weight	150.48 pcf
Max. C.A. Size	1 in.			Meas. Unit Weight	152.72 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.89
Water	12.61	0.69	1.00	43.27	-3.03	40.23	-3.93	36.30	39.34	0.63	11.65
F.A.	26.36	1.45	2.59	234.34	+6.21	240.55	+0.05	240.60	234.38	1.45	26.80
C.A.	46.30	2.55	2.74	435.35	-3.18	432.17	+0.03	432.20	435.38	2.55	47.06
Air	5.00	0.28								0.25	4.60
Totals	100.00	5.50		818.19		818.19		814.30	814.30	5.41	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 7, Batch 2.

		Design Values		Actual Values	
Date	06/02/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.59 sk/cy
Mix Design Number	4	Air Content	5.00 %	Air Content	3.80 %
F.A. Moisture Content	+2.65 %	C.A. Factor	0.76	C.A. Factor	0.77
C.A. Moisture Content	-0.73 %	W/C Ratio	0.41	W/C Ratio	0.40
Air Entraining Agent	66 mL	Slump	1-1/2 in.	Slump	1-1/2 in.
Air Temperature	87°F	Unit Weight	148.76 pcf	Calc. Unit Weight	151.04 pcf
Max. C.A. Size	1 in.			Meas. Unit Weight	154.18 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.90
Water	12.61	0.69	1.00	43.27	-3.03	40.23	-1.43	38.80	41.84	0.67	12.40
F.A.	26.36	1.45	2.59	234.34	+6.21	240.55	+0.05	240.60	234.38	1.45	26.82
C.A.	46.30	2.55	2.74	435.35	-3.18	432.17	+0.03	432.20	435.38	2.55	47.09
Air	5.00	0.28								0.21	3.80
Totals	100.00	5.50		818.19		818.19		816.80	816.80	5.41	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 7, Batch 3.

		Design Values		Actual Values	
Date	06/02/83				
Mix Design Number	4				
F.A. Moisture Content	+2.65 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.59 sk/cy
C.A. Moisture Content	-0.73 %	Air Content	5.00 %	Air Content	4.20 %
Air Entraining Agent	66 mL	C.A. Factor	0.76	C.A. Factor	0.77
Air Temperature	87°F	W/C Ratio	0.41	W/C Ratio	0.38
Max. C.A. Size	1 in.	Slump	1-1/2 in.	Slump	1-1/2 in.
		Unit Weight	148.76 pcf	Calc. Unit Weight	150.80 pcf
				Meas. Unit Weight	153.12 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.90
Water	12.61	0.69	1.00	43.27	-3.03	40.23	-2.83	37.40	40.44	0.65	11.99
F.A.	26.36	1.45	2.59	234.34	+6.21	240.55	+0.05	240.60	234.38	1.45	26.82
C.A.	46.30	2.55	2.74	435.35	-3.18	432.17	+0.03	432.20	435.38	2.55	47.09
Air	5.00	0.28								0.23	4.20
Totals	100.00	5.50		818.19		818.19		815.40	815.40	5.41	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 7, Batch 4.

		Design Values		Actual Values	
Date	06/02/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.56 sk/cy
Mix Design Number	4	Air Content	5.00 %	Air Content	4.00 %
F.A. Moisture Content	+2.65 %	C.A. Factor	0.76	C.A. Factor	0.77
C.A. Moisture Content	-0.73 %	W/C Ratio	0.41	W/C Ratio	0.41
Air Entraining Agent	66 ml.	Slump	1-1/2 in.	Slump	1-1/4 in.
Air Temperature	87°F	Unit Weight	148.76 pcf	Calc. Unit Weight	150.34 pcf
Max. C.A. Size	1 in.			Meas. Unit Weight	153.43 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.83
Water	12.61	0.69	1.00	43.27	-3.03	40.23	-0.03	40.20	43.24	0.69	12.73
F.A.	26.36	1.45	2.59	234.34	+6.21	240.55	+0.05	240.60	234.38	1.45	26.65
C.A.	46.30	2.55	2.74	435.35	-3.18	432.17	+0.03	432.20	435.38	2.55	46.79
Air	5.00	0.28								0.22	4.00
Totals	100.00	5.50		818.19		818.19		818.20	818.20	5.44	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 8, Batch 1.

Date	06/16/83
Mix Design Number	5
F.A. Moisture Content	+2.29 %
C.A. Moisture Content	-0.91 %
Air Entraining Agent	66 ml.
Air Temperature	89°F
Max. C.A. Size	3/4 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	1-1/2 in.
Unit Weight	148.76 pcf

Actual Values	
Cem. Factor	5.51 sk/cy
Air Content	4.80 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	1-1/2 in.
Calc. Unit Weight	149.06 pcf
Meas. Unit Weight	153.47 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.75
Water	12.61	0.69	1.00	43.27	-1.40	41.86	+0.04	41.90	43.31	0.69	12.64
F.A.	26.36	1.45	2.59	234.34	+5.37	239.70	+0.00	239.70	234.34	1.45	26.42
C.A.	46.30	2.55	2.74	435.35	-3.96	431.39	+0.01	431.40	435.36	2.55	46.39
Air	5.00	0.28								0.26	4.80
Totals	100.00	5.50		818.19		818.19		818.20	818.20	5.49	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 8, Batch 2.

Date	06/16/83
Mix Design Number	5
F.A. Moisture Content	+2.29 %
C.A. Moisture Content	-0.91 %
Air Entraining Agent	66 mL
Air Temperature	89°F
Max. C.A. Size	3/4 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	1-1/2 in.
Unit Weight	148.76 pcf

Actual Values	
Cem. Factor	5.53 sk/cy
Air Content	4.40 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	2 in.
Calc. Unit Weight	149.69 pcf
Meas. Unit Weight	152.24 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.79
Water	12.61	0.69	1.00	43.27	-1.40	41.86	+0.04	41.90	43.31	0.69	12.70
F.A.	26.36	1.45	2.59	234.34	+5.37	239.70	+0.00	239.70	234.34	1.45	26.53
C.A.	46.30	2.55	2.74	435.35	-3.96	431.39	+0.01	431.40	435.36	2.55	46.58
Air	5.00	0.28								0.24	4.40
Totals	100.00	5.50		818.19		818.19		818.20	818.20	5.47	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 8, Batch 3.

Date	06/16/83
Mix Design Number	5
F.A. Moisture Content	+2.29 %
C.A. Moisture Content	-0.91 %
Air Entraining Agent	66 ml.
Air Temperature	89°F
Max. C.A. Size	3/4 in.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.76
W/C Ratio	0.41
Slump	1-1/2 in.
Unit Weight	148.76 pcf

Actual Values	
Cem. Factor	5.54 sk/cy
Air Content	4.30 %
C.A. Factor	0.77
W/C Ratio	0.41
Slump	1-1/4 in.
Calc. Unit Weight	149.85 pcf
Meas. Unit Weight	152.50 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.80
Water	12.61	0.69	1.00	43.27	-1.40	41.86	+0.04	41.90	43.31	0.69	12.71
F.A.	26.36	1.45	2.59	234.34	+5.37	239.70	+0.00	239.70	234.34	1.45	26.55
C.A.	46.30	2.55	2.74	435.35	-3.96	431.39	+0.01	431.40	435.36	2.55	46.63
Air	5.00	0.28								0.23	4.30
Totals	100.00	5.50		818.19		818.19		818.20	818.20	5.46	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 8, Batch 4.

		Design Values		Actual Values	
Date	06/16/83				
Mix Design Number	5	Cem. Factor	5.50 sk/cy	Cem. Factor	5.53 sk/cy
F.A. Moisture Content	+2.29 %	Air Content	5.00 %	Air Content	4.40 %
C.A. Moisture Content	-0.91 %	C.A. Factor	0.76	C.A. Factor	0.76
Air Entraining Agent	66 mL	W/C Ratio	0.41	W/C Ratio	0.41
Air Temperature	89°F	Slump	1-1/2 in.	Slump	1-1/2 in.
Max. C.A. Size	3/4 in.	Unit Weight	148.76 pcf	Calc. Unit Weight	149.69 pcf
				Meas. Unit Weight	N/A

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.79
Water	12.61	0.69	1.00	43.27	-1.40	41.86	+0.04	41.90	43.31	0.69	12.70
F.A.	26.36	1.45	2.59	234.34	+5.37	239.70	+0.00	239.70	234.34	1.45	26.53
C.A.	46.30	2.55	2.74	435.35	-3.96	431.39	+0.01	431.40	435.36	2.55	46.58
Air	5.00	0.28								0.24	4.40
Totals	100.00	5.50		818.19		818.19		818.20	818.20	5.47	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 9, Batch 1.

		Design Values		Actual Values	
Date	05/25/83				
Mix Design Number	6				
F.A. Moisture Content	+2.64 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.66 sk/cy
C.A. Moisture Content	-0.94 %	Air Content	5.00 %	Air Content	3.20 %
Air Entraining Agent	66 mL	C.A. Factor	0.80	C.A. Factor	0.82
Air Temperature	82°F	W/C Ratio	0.34	W/C Ratio	0.31
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/4 in.
Superplas. Agent	365 mL	Unit Weight	151.05 pcf	Calc. Unit Weight . .	154.91 pcf
				Meas. Unit Weight . .	156.24 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	10.02
Water	10.53	0.58	1.00	36.15	-1.79	34.36	-3.46	30.90	32.69	0.52	9.81
F.A.	26.00	1.43	2.59	231.10	+6.10	237.20	+0.00	237.20	231.10	1.43	26.78
C.A.	48.73	2.68	2.74	458.26	-4.31	453.95	+0.05	454.00	458.31	2.68	50.19
Air	5.00	0.28								0.17	3.20
Totals	100.00	5.50		830.76		830.76		827.31	827.31	5.34	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 9, Batch 2.

Date	05/25/83
Mix Design Number	6
F.A. Moisture Content	+2.64 %
C.A. Moisture Content	-0.94 %
Air Entraining Agent	66 ml.
Air Temperature	82°F
Max. C.A. Size	1-1/2 in.
Superplas. Agent	365 ml.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.34
Slump	1-1/2 in.
Unit Weight	151.05 pcf

Actual Values	
Cem. Factor	5.63 sk/cy
Air Content	3.40 %
C.A. Factor	0.82
W/C Ratio	0.32
Slump	2 in.
Calc. Unit Weight . .	154.21 pcf
Meas. Unit Weight . .	155.89 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.96
Water	10.53	0.58	1.00	36.15	-1.79	34.36	-2.16	32.20	33.99	0.54	10.14
F.A.	26.00	1.43	2.59	231.10	+6.10	237.20	+0.00	237.20	231.10	1.43	26.61
C.A.	48.73	2.68	2.74	458.26	-4.31	453.95	+0.05	454.00	458.31	2.68	49.89
Air	5.00	0.28								0.18	3.40
Totals	100.00	5.50		830.76		830.76		827.31	827.31	5.37	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 9, Batch 3.

		Design Values		Actual Values	
Date	05/25/83				
Mix Design Number	6				
F.A. Moisture Content	+2.64 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.61 sk/cy
C.A. Moisture Content	–0.94 %	Air Content	5.00 %	Air Content	3.40 %
Air Entraining Agent	66 mL	C.A. Factor	0.80	C.A. Factor	0.82
Air Temperature	82°F	W/C Ratio	0.34	W/C Ratio	0.33
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/4 in.
Superplas. Agent	365 mL	Unit Weight	151.05 pcf	Calc. Unit Weight	153.89 pcf
				Meas. Unit Weight	154.92 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	–0.04	105.20	105.20	0.54	9.93
Water	10.53	0.58	1.00	36.15	-1.79	34.36	-1.06	33.30	35.09	0.56	10.43
F.A.	26.00	1.43	2.59	231.10	+6.10	237.20	+0.00	237.20	231.10	1.43	26.52
C.A.	48.73	2.68	2.74	458.26	-4.31	453.95	+0.05	454.00	458.31	2.68	49.72
Air	5.00	0.28								0.18	3.40
Totals	100.00	5.50		830.76		830.76		829.71	829.71	5.39	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 9, Batch 4.

Date	05/25/83	Design Values		Actual Values	
Mix Design Number	6				
F.A. Moisture Content	+2.64 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.58 sk/cy
C.A. Moisture Content	-0.94 %	Air Content	5.00 %	Air Content	3.60 %
Air Entraining Agent	66 mL	C.A. Factor	0.80	C.A. Factor	0.81
Air Temperature	82°F	W/C Ratio	0.34	W/C Ratio	0.34
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	2 in.
Superplas. Agent	365 mL	Unit Weight	151.05 pcf	Calc. Unit Weight	153.26 pcf
				Meas. Unit Weight	156.26 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.87
Water	10.53	0.58	1.00	36.15	-1.79	34.36	+0.04	34.40	36.19	0.58	10.70
F.A.	26.00	1.43	2.59	231.10	+6.10	237.20	+0.00	237.20	231.10	1.43	26.38
C.A.	48.73	2.68	2.74	458.26	-4.31	453.95	+0.05	454.00	458.31	2.68	49.45
Air	5.00	0.28								0.20	3.60
Totals	100.00	5.50		830.76		830.76		830.81	830.81	5.42	100.00

Note: Vibrators spaced at 18 in. and moved parallel to the direction of travel.

Test 10, Batch 1.

		Design Values		Actual Values	
Date	05/26/83				
Mix Design Number	6				
F.A. Moisture Content	+5.23 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.52 sk/cy
C.A. Moisture Content	-0.96 %	Air Content	5.00 %	Air Content	4.60 %
Air Entraining Agent	66 mL	C.A. Factor	0.80	C.A. Factor	0.80
Air Temperature	83°F	W/C Ratio	0.34	W/C Ratio	0.34
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/2 in.
Superplas. Agent	365 mL	Unit Weight	151.05 pcf	Calc. Unit Weight	151.67 pcf
				Meas. Unit Weight	155.58 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.77
Water	10.53	0.58	1.00	36.15	-7.69	28.47	+0.03	28.50	36.18	0.58	10.59
F.A.	26.00	1.43	2.59	231.10	+12.09	243.19	+0.01	243.20	231.11	1.43	26.11
C.A.	48.73	2.68	2.74	458.26	-4.40	453.86	+0.04	453.90	458.30	2.68	48.94
Air	5.00	0.28								0.25	4.60
Totals	100.00	5.50		830.76		830.76		830.80	830.80	5.48	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 10, Batch 2.

		Design Values		Actual Values	
Date	05/26/83				
Mix Design Number	6				
F.A. Moisture Content	+5.23 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.57 sk/cy
C.A. Moisture Content	-0.96 %	Air Content	5.00 %	Air Content	3.80 %
Air Entraining Agent	66 mL	C.A. Factor	0.80	C.A. Factor	0.81
Air Temperature	83°F	W/C Ratio	0.34	W/C Ratio	0.34
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	1-1/2 in.
Superplas. Agent	365 mL	Unit Weight	151.05 pcf	Calc. Unit Weight	152.95 pcf
				Meas. Unit Weight	157.61 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.85
Water	10.53	0.58	1.00	36.15	-7.69	28.47	+0.03	28.50	36.18	0.58	10.67
F.A.	26.00	1.43	2.59	231.10	+12.09	243.19	+0.01	243.20	231.11	1.43	26.33
C.A.	48.73	2.68	2.74	458.26	-4.40	453.86	+0.04	453.90	458.30	2.68	49.35
Air	5.00	0.28								0.21	3.80
Totals	100.00	5.50		830.76		830.76		830.80	830.80	5.43	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 10, Batch 3.

		Design Values		Actual Values	
Date	05/26/83				
Mix Design Number	6				
F.A. Moisture Content	+5.23 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.57 sk/cy
C.A. Moisture Content	-0.96 %	Air Content	5.00 %	Air Content	3.80 %
Air Entraining Agent	66 ml.	C.A. Factor	0.80	C.A. Factor	0.81
Air Temperature	83°F	W/C Ratio	0.34	W/C Ratio	0.34
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	2 in.
Superplas. Agent	365 ml.	Unit Weight	151.05 pcf	Calc. Unit Weight	152.95 pcf
				Meas. Unit Weight	155.14 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.85
Water	10.53	0.58	1.00	36.15	-7.69	28.47	+0.03	28.50	36.18	0.58	10.67
F.A.	26.00	1.43	2.59	231.10	+12.09	243.19	+0.01	243.20	231.11	1.43	26.33
C.A.	48.73	2.68	2.74	458.26	-4.40	453.86	+0.04	453.90	458.30	2.68	49.35
Air	5.00	0.28								0.21	3.80
Totals	100.00	5.50		830.76		830.76		830.80	830.80	5.43	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 10, Batch 4.

Date	05/26/83
Mix Design Number	6
F.A. Moisture Content	+5.23 %
C.A. Moisture Content	-0.96 %
Air Entraining Agent	66 mL
Air Temperature	83°F
Max. C.A. Size	1-1/2 in.
Superplas. Agent	365 mL

Design Values

Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.34
Slump	1-1/2 in.
Unit Weight	151.05 pcf

Actual Values

Cem. Factor	5.56 sk/cy
Air Content	4.00 %
C.A. Factor	0.81
W/C Ratio	0.34
Slump	1-1/2 in.
Calc. Unit Weight ..	152.63 pcf
Meas. Unit Weight ..	155.45 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.83
Water	10.53	0.58	1.00	36.15	-7.69	28.47	+0.03	28.50	36.18	0.58	10.65
F.A.	26.00	1.43	2.59	231.10	+12.09	243.19	+0.01	243.20	231.11	1.43	26.27
C.A.	48.73	2.68	2.74	458.26	-4.40	453.86	+0.04	453.90	458.30	2.68	49.24
Air	5.00	0.28								0.22	4.00
Totals	100.00	5.50		830.76		830.76		830.80	830.80	5.44	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 11, Batch 1.

Date	07/16/83
Mix Design Number	6
F.A. Moisture Content	+3.90 %
C.A. Moisture Content	+0.34 %
Air Entraining Agent	66 mL
Air Temperature	80.6°F
Max. C.A. Size	1-1/2 in.
Super/Retarder Agent	365 mL

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.34
Slump	1-1/2 in.
Unit Weight	151.05 pcf

Actual Values	
Cem. Factor	5.44 sk/cy
Air Content	5.40 %
C.A. Factor	0.79
W/C Ratio	0.36
Slump	1 in.
Calc. Unit Weight	149.87 pcf
Meas. Unit Weight	154.35 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.63
Water	10.53	0.58	1.00	36.15	-10.57	25.58	+1.92	27.50	38.07	0.61	10.98
F.A.	26.00	1.43	2.59	231.10	+9.01	240.11	-0.01	240.10	231.09	1.43	25.74
C.A.	48.73	2.68	2.74	458.26	+1.56	459.82	-0.02	459.80	458.24	2.68	48.24
Air	5.00	0.28								0.30	5.40
Totals	100.00	5.50		830.76		830.76		832.61	832.61	5.56	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 11, Batch 2.

Date	07/16/83
Mix Design Number	6
F.A. Moisture Content	+3.90 %
C.A. Moisture Content	+0.34 %
Air Entraining Agent	66 ml.
Air Temperature	80.6°F
Max. C.A. Size	1-1/2 in.
Super/Retarder Agent	365 ml.

Design Values	
Cem. Factor	5.50 sk/cy
Air Content	5.00 %
C.A. Factor	0.80
W/C Ratio	0.34
Slump	1-1/2 in.
Unit Weight	151.05 pcf

Actual Values	
Cem. Factor	5.54 sk/cy
Air Content	5.00 %
C.A. Factor	0.81
W/C Ratio	0.32
Slump	2-1/2 in.
Calc. Unit Weight	151.75 pcf
Meas. Unit Weight	154.18 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.81
Water	10.53	0.58	1.00	36.15	-10.57	25.58	-2.48	23.10	33.67	0.54	9.89
F.A.	26.00	1.43	2.59	231.10	+9.01	240.11	-0.01	240.10	231.09	1.43	26.20
C.A.	48.73	2.68	2.74	458.26	+1.56	459.82	-0.02	459.80	458.24	2.68	49.11
Air	5.00	0.28								0.27	5.00
Totals	100.00	5.50		830.76		830.76		828.21	828.21	5.46	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 11, Batch 3.

		Design Values		Actual Values	
Date	07/16/83				
Mix Design Number	6				
F.A. Moisture Content	+3.90 %	Cem. Factor	5.50 sk/cy	Cem. Factor	5.53 sk/cy
C.A. Moisture Content	+0.34 %	Air Content	5.00 %	Air Content	5.60 %
Air Entraining Agent	66 ml.	C.A. Factor	0.80	C.A. Factor	0.81
Air Temperature	80.6 °F	W/C Ratio	0.34	W/C Ratio	0.30
Max. C.A. Size	1-1/2 in.	Slump	1-1/2 in.	Slump	3-1/2 in.
Super/Retarder Agent	365 ml.	Unit Weight	151.05 pcf	Calc. Unit Weight	151.28 pcf
				Meas. Unit Weight	153.47 pcf

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.80
Water	10.53	0.58	1.00	36.15	-10.57	25.58	-4.18	21.40	31.97	0.51	9.38
F.A.	26.00	1.43	2.59	231.10	+9.01	240.11	-0.01	240.10	231.09	1.43	26.17
C.A.	48.73	2.68	2.74	458.26	+1.56	459.82	-0.02	459.80	458.24	2.68	49.05
Air	5.00	0.28								0.31	5.60
Totals	100.00	5.50		830.76		830.76		826.51	826.51	5.46	100.00

Note: Vibrator moved perpendicular to the direction of travel.

Test 11, Batch 4.

		Design Values		Actual Values	
Date	07/16/83	Cem. Factor	5.50 sk/cy	Cem. Factor	5.46 sk/cy
Mix Design Number	6	Air Content	5.00 %	Air Content	5.60 %
F.A. Moisture Content	+3.90 %	C.A. Factor	0.80	C.A. Factor	0.79
C.A. Moisture Content	+0.34 %	W/C Ratio	0.34	W/C Ratio	0.34
Air Entraining Agent	66 ml.	Slump	1-1/2 in.	Slump	1-3/4 in.
Air Temperature	80.6°F	Unit Weight	151.05 pcf	Calc. Unit Weight	150.09 pcf
Max. C.A. Size	1-1/2 in.			Meas. Unit Weight	153.25 pcf
Super/Retarder Agent	365 ml.				

Mat'l	Design Abs Vol (%)	Design Abs Vol (cu.ft.)	Spec Grav	Design SSD Wt (lb)	Water Adjust (lb)	Design Btch Wt (lb)	Weight Adjust (lb)	Actual Btch Wt (lb)	Actual SSD Wt (lb)	Actual Abs Vol (cu.ft.)	Actual Abs Vol (%)
Cem.	9.74	0.54	3.15	105.24		105.24	-0.04	105.20	105.20	0.54	9.67
Water	10.53	0.58	1.00	36.15	-10.57	25.58	+0.02	25.60	36.17	0.58	10.47
F.A.	26.00	1.43	2.59	231.10	+9.01	240.11	-0.01	240.10	231.09	1.43	25.83
C.A.	48.73	2.68	2.74	458.26	+1.56	459.82	-0.02	459.80	458.24	2.68	48.42
Air	5.00	0.28								0.31	5.60
Totals	100.00	5.50		830.76		830.76		830.71	830.71	5.53	100.00

Note: Vibrator moved perpendicular to the direction of travel.

APPENDIX D

CYLINDER AND BEAM TEST RESULTS

Compressive strength results (psi).

Test No.	Batch 1	Batch 2	Batch 3	Batch 4	Average
1	4560	4850	6080	5440	5230
2	5300	5550	5190	4940	5250
3	5040	4680	4820	4620	4790
4	5280	4370	3830	4840	4580
5	3810	4330	5080	5110	4580
6	5290	3970	5220	5100	4890
7	4700	5430	5360	5190	5170
8	5440	4180	4680	4990	4820
9	5460	7300	6970	6280	6500
10	5810	6620	5320	7300	6260
11	5630	5090	6000	5030	5440

Modulus of Rupture results (psi).

Test No.	Batch 1	Batch 2	Batch 3	Batch 4	Average
1	1100	1060	1130	955	1060
2			1135		1135
3	1000		970		985
4	910		890		900
5	775		870		820
6	960			1065	1015
7	1010		1040		1025
8		870		890	880
9		1180	1090		1135
10		1065			1065
11			900	1075	990

Note: Test 1 consisted of casting one beam for each batch. All other tests consisted of casting one beam from each of two randomly selected batches within the tests. Each beam was broken twice, therefore, all entries in the Batch columns are averages of two values.

APPENDIX E

RESULTS OF THE CORE ANALYSIS

Test 1 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	8.74	148.8	154.2	40	485
1AM	8.88				
1AB	7.31	151.6	156.2	70	700
1BT	8.74	148.7	154.2	30	505
1BM	8.32	149.7	154.8		
1BB	7.35	150.5	155.1	70	815
1CT	8.84	148.9	154.4	30	530
1CM	8.55				
1CB	7.66	150.2	155.0	60	625
2AT	8.81	149.7	155.2	10	505
2AM	8.59				
2AB	7.73	149.8	154.7	80	805
2BT	8.97	148.9	154.5	30	570
2BM	8.78	147.1	152.6		
2BB	7.47	150.3	155.0	70	765
2CT	9.03	149.0	154.6	10	555
2CM	9.64				
2CB	7.62	149.6	154.4	90	660
3AT	8.70	149.7	155.1	50	605
3AM	8.39				
3AB	6.98	152.3	156.7	50	755
3BT	8.57	149.2	154.5	50	555
3BM	8.38	147.7	152.9		
3BB	7.76	148.5	153.4	80	880
3CT	8.62	148.8	154.2	60	625
3CM	8.78				
3CB	7.66	146.8	151.6	70	745
4AT	8.86	147.8	153.3	70	650
4AM	8.44				
4AB	7.38	145.6	150.2	60	840
4BT	8.74	148.9	154.3	10	610
4BM	7.96	146.3	151.3		
4BB	7.81	144.9	149.8	N/A	N/A
4CT	10.01	140.9	147.2	40	430
4CM	7.90				
4CB	8.81	148.6	154.04	70	N/A

N/A - not available

Test 2 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	8.64	149.6	155.0	10	390
1AM	7.93				
1AB	6.99	152.5	156.8	50	680
1BT	8.99	148.3	153.9	30	595
1BM	N/A	N/A	N/A		
1BB	7.33	149.8	154.4	90	855
1CT	9.14	150.5	156.2	N/A	N/A
1CM	8.68				
1CB	7.53	151.0	155.7	90	760
2AT	9.62	146.2	152.2	30	525
2AM	8.84				
2AB	7.13	151.8	156.3	50	770
2BT	9.30	148.2	154.0	20	545
2BM	8.83	148.5	154.0		
2BB	7.01	152.7	157.1	70	795
2CT	8.83	148.9	154.4	30	560
2CM	9.14				
2CB	7.26	152.5	157.0	50	740
3AT	9.07	147.7	153.4	20	510
3AM	8.87				
3AB	7.24	151.7	156.2	50	725
3BT	8.67	149.5	154.9	40	515
3BM	8.98	147.2	152.8		
3BB	8.05	149.7	154.8	50	695
3CT	8.93	148.6	154.1	50	480
3CM	8.65				
3CB	7.26	153.0	157.5	70	700
4AT	9.03	147.9	153.6	N/A	N/A
4AM	8.78				
4AB	7.21	152.4	156.9	50	715
4BT	9.07	147.4	153.1	50	590
4BM	8.53	148.0	153.3		
4BB	7.32	151.9	156.5	70	905
4CT	8.57	148.8	154.2	10	605
4CM	8.15				
4CB	8.23	150.8	155.9	50	765

Test 3 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	7.78	153.5	158.4	20	425
1AM	7.87				
1AB	6.46	154.8	158.8	30	565
1BT	8.74	150.9	156.3	20	475
1BM	8.81	150.7	156.2		
1BB	6.37	154.8	158.0	40	630
1CT	8.94	151.8	157.4	20	455
1CM	8.48				
1CB	6.78	152.1	156.3	40	535
2AT	8.38	151.9	157.2	40	415
2AM	9.00				
2AB	6.80	154.0	158.3	50	850
2BT	8.18	153.1	158.2	20	465
2BM	8.20	152.0	157.2		
2BB	7.54	150.5	155.2	60	895
2CT	8.40	152.9	158.2	40	620
2CM	8.22				
2CB	7.07	153.5	157.9	30	715
3AT	9.00	149.9	155.5	10	625
3AM	9.33				
3AB	7.35	152.5	157.1	60	1000
3BT	9.39	149.9	155.7	40	555
3BM	9.21	149.2	155.0		
3BB	7.41	153.2	157.8	50	765
3CT	8.79	151.5	157.0	40	555
3CM	9.29				
3CB	7.70	151.7	156.5	60	660
4AT	6.81	153.4	157.7	80	740
4AM	8.20				
4AB	8.98	149.8	155.4	20	530
4BT	8.89	148.7	154.3	30	530
4BM	8.23	149.3	154.4		
4BB	7.28	151.5	156.1	70	765
4CT	9.02	147.8	153.5	10	435
4CM	8.04				
4CB	8.46	148.8	154.1	80	510

Test 4 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	5.80	154.1	157.7	30	450
1AM	5.51				
1AB	7.20	149.2	153.7	80	585
1BT	6.52	153.4	157.5	40	550
1BM	5.96	158.9	162.6		
1BB	9.73	147.9	154.0	N/A	N/A
1CT	7.24	152.0	156.5	10	540
1CM	6.09				
1CB	9.73	148.0	154.1	N/A	N/A
2AT	8.03	150.0	155.0	20	430
2AM	6.95				
2AB	5.64	153.1	156.6	50	715
2BT	7.32	152.6	157.2	70	520
2BM	6.52	150.6	154.7		
2BB	6.00	150.4	154.1	N/A	530
2CT	7.13	151.3	155.8	50	430
2CM	7.27				
2CB	4.67	152.2	155.1	40	390
3AT	N/A	N/A	N/A	N/A	N/A
3AM	N/A				
3AB	N/A	N/A	N/A	N/A	N/A
3BT	9.63	150.0	156.0	20	560
3BM	9.47	149.7	155.6		
3BB	7.83	152.1	157.0	70	485
3CT	7.73	150.6	155.4	60	520
3CM	6.28				
3CB	5.09	152.1	155.3	80	525
4AT	9.57	150.5	156.5	10	385
4AM	9.35				
4AB	6.89	154.9	159.2	90	390
4BT	7.48	150.8	155.4	60	435
4BM	5.32	154.3	157.6		
4BB	5.53	153.6	157.1	90	685
4CT	8.78	149.6	155.1	40	445
4CM	6.68				
4CB	5.96	153.7	157.4	80	520

Test 5 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	10.17	145.2	151.5	N/A	N/A
1AM	8.70				
1AB	9.61	N/A	N/A	70	720
1BT	10.22	144.7	151.1	30	425
1BM	8.89	145.8	151.4		
1BB	7.93	147.8	152.8	70	505
1CT	9.71	145.2	151.3	10	370
1CM	8.37				
1CB	8.01	149.4	154.4	60	705
2AT	9.75	146.7	152.7	50	635
2AM	8.88				
2AB	7.61	149.7	154.4	N/A	N/A
2BT	9.24	148.4	154.2	50	490
2BM	8.56	148.9	154.2		
2BB	7.95	148.4	153.4	50	795
2CT	9.26	148.5	154.3	40	315
2CM	8.89				
2CB	8.01	149.6	154.6	80	565
3AT	9.19	148.2	153.9	20	410
3AM	8.85				
3AB	7.52	150.4	155.1	N/A	N/A
3BT	9.75	147.0	153.1	30	505
3BM	8.81	148.1	153.5		
3BB	8.12	148.0	153.1	40	820
3CT	9.09	149.3	155.0	60	525
3CM	9.56				
3CB	8.32	149.2	154.4	60	730
4AT	8.68	149.8	155.2	20	550
4AM	8.85				
4AB	8.48	148.6	153.9	90	570
4BT	9.62	145.7	151.7	10	445
4BM	9.63	153.0	159.0		
4BB	7.95	149.4	154.4	70	815
4CT	9.66	146.1	152.1	60	520
4CM	9.21				
4CB	7.70	151.7	156.5	30	860

Test 6 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	8.11	151.4	156.5	30	345
1AM	8.53				
1AB	9.95	148.4	154.6	N/A	N/A
1BT	7.86	153.6	158.6	30	560
1BM	8.86	155.9	161.5		
1BB	9.51	147.8	153.8	N/A	N/A
1CT	8.82	150.8	156.3	10	355
1CM	8.17				
1CB	7.44	152.8	157.4	80	830
2AT	9.97	147.5	153.7	30	410
2AM	8.95				
2AB	7.62	152.5	157.2	70	665
2BT	9.48	149.1	155.0	20	365
2BM	8.60	150.2	155.6		
2BB	7.96	152.2	157.2	70	630
2CT	10.10	147.1	153.5	20	425
2CM	10.26				
2CB	8.95	148.8	154.4	30	675
3AT	9.56	148.4	154.3	30	490
3AM	8.78				
3AB	7.54	152.7	157.4	70	605
3BT	8.84	149.9	155.4	20	530
3BM	8.56	150.1	155.5		
3BB	7.58	151.6	156.4	60	615
3CT	8.68	150.6	156.0	60	525
3CM	8.92				
3CB	7.55	152.9	157.6	80	815
4AT	8.48	151.3	156.6	N/A	N/A
4AM	N/A				
4AB	9.85	146.7	152.9	N/A	N/A
4BT	8.61	151.4	156.7	30	485
4BM	8.29	151.6	156.8		
4BB	8.27	153.3	158.4	N/A	N/A
4CT	8.46	151.5	156.8	20	515
4CM	8.18				
4CB	7.00	155.3	159.7	90	690

Test 7 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	9.17	148.5	154.2	20	460
1AM	8.53				
1AB	7.86	148.7	153.6	70	635
1BT	9.60	146.7	152.7	30	455
1BM	8.81	148.6	154.1		
1BB	7.42	150.3	154.9	80	605
1CT	9.77	147.2	153.3	20	465
1CM	8.59				
1CB	7.66	150.4	155.2	80	695
2AT	9.89	145.3	151.5	10	415
2AM	9.32				
2AB	7.90	148.5	153.4	50	590
2BT	9.51	146.2	152.1	40	485
2BM	9.00	146.7	152.3		
2BB	7.41	147.9	152.5	70	535
2CT	9.37	146.3	152.1	20	465
2CM	9.02				
2CB	8.09	150.4	155.4	40	725
3AT	9.47	146.7	152.6	60	435
3AM	9.13				
3AB	7.32	150.9	155.5	80	630
3BT	9.46	147.3	153.2	50	465
3BM	9.17	147.7	153.5		
3BB	7.70	150.6	155.4	80	680
3CT	9.38	148.0	153.8	50	520
3CM	9.26				
3CB	7.89	149.1	154.1	80	700
4AT	10.34	146.7	153.1	30	485
4AM	7.60				
4AB	5.80	152.5	156.2	80	590
4BT	9.47	148.5	154.4	50	455
4BM	9.38	146.3	152.2		
4BB	8.16	149.7	154.8	70	560
4CT	8.48	149.6	154.8	10	455
4CM	9.05				
4CB	10.38	146.2	152.7	80	415

Test 8 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	8.68	148.2	153.6	40	505
1AM	6.62				
1AB	7.32	148.4	153.0	60	605
1BT	9.01	147.7	153.3	50	520
1BM	6.58	149.0	153.1		
1BB	7.53	148.3	153.0	50	670
1CT	10.40	145.1	151.6	20	490
1CM	9.63				
1CB	12.13	140.7	148.2	N/A	N/A
2AT	9.82	145.5	151.6	10	405
2AM	9.36				
2AB	7.81	149.3	154.2	70	720
2BT	10.23	145.0	151.4	40	450
2BM	9.30	145.6	151.4		
2BB	N/A	N/A	N/A	N/A	N/A
2CT	9.71	144.7	150.8	40	490
2CM	9.29				
2CB	N/A	N/A	N/A	N/A	N/A
3AT	9.80	144.8	150.1	20	515
3AM	9.59				
3AB	7.56	148.6	153.4	50	750
3BT	9.65	146.2	152.3	20	460
3BM	9.40	146.0	151.9		
3BB	7.58	148.3	153.0	50	655
3CT	9.73	145.8	151.8	30	585
3CM	9.66				
3CB	8.12	149.4	154.5	50	650
4AT	10.14	145.8	152.1	30	585
4AM	9.47				
4AB	8.31	149.0	154.2	80	705
4BT	8.40	147.5	152.8	30	520
4BM	6.27	148.5	152.4		
4BB	6.21	149.9	153.8	80	765
4CT	7.36	148.8	153.4	80	625
4CM	7.02				
4CB	7.10	149.0	153.4	80	500

Test 9 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	7.07	153.2	157.6	40	555
1AM	7.07				
1AB	9.15	142.9	148.6	N/A	N/A
1BT	7.72	150.5	155.3	50	655
1BM	6.70	150.6	154.8		
1BB	7.46	147.2	151.9	30	700
1CT	7.45	151.2	155.8	50	690
1CM	6.95				
1CB	9.27	144.8	150.6	N/A	N/A
2AT	7.88	151.9	156.9	20	705
2AM	7.33				
2AB	8.33	148.4	153.6	60	480
2BT	7.56	153.0	157.8	30	695
2BM	7.76	149.5	154.3		
2BB	7.27	152.7	157.3	90	625
2CT	7.89	151.3	156.2	30	700
2CM	7.78				
2CB	6.15	154.1	157.9	90	960
3AT	7.98	150.5	155.5	30	690
3AM	7.87				
3AB	5.71	155.5	159.0	70	675
3BT	7.76	152.8	157.7	80	670
3BM	8.11	166.5	171.6		
3BB	6.04	153.4	157.2	90	700
3CT	8.07	150.6	155.6	30	640
3CM	7.40				
3CB	6.71	153.2	157.4	70	760
4AT	8.01	151.9	156.9	20	690
4AM	7.81				
4AB	5.80	156.2	159.8	60	930
4BT	8.25	150.5	155.7	40	735
4BM	7.84	150.6	155.5		
4BB	6.75	152.6	156.8	90	940
4CT	8.08	151.5	156.5	50	690
4CM	7.39				
4CB	9.05	148.5	154.1	60	305

Test 10 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	6.85	153.1	157.4	80	735
1AM	7.73				
1AB	7.73	148.3	153.1	50	670
1BT	6.68	154.8	159.0	20	660
1BM	6.78	152.6	156.8		
1BB	6.73	150.1	154.3	90	870
1CT	7.49	151.9	156.6	30	615
1CM	6.99				
1CB	7.73	148.7	153.6	50	535
2AT	7.25	153.2	157.8	40	590
2AM	2.85				
2AB	6.65	151.7	155.8	90	860
2BT	7.29	152.6	157.2	70	650
2BM	7.03	153.0	157.4		
2BB	7.21	151.9	156.4	70	925
2CT	7.23	153.4	157.9	50	565
2CM	7.21				
2CB	8.18	148.0	153.1	70	630
3AT	8.16	150.3	155.4	40	590
3AM	7.61				
3AB	7.31	149.0	153.6	80	560
3BT	8.17	150.6	155.7	20	615
3BM	7.73	147.2	152.0		
3BB	7.10	145.0	149.4	80	645
3CT	8.30	149.7	154.9	20	575
3CM	7.99				
3CB	7.27	146.3	150.8	70	610
4AT	7.34	152.1	156.7	30	585
4AM	7.47				
4AB	6.87	148.9	153.1	90	840
4BT	7.69	152.7	157.5	60	750
4BM	7.18	151.5	155.9		
4BB	7.58	151.1	155.8	50	845
4CT	7.19	153.0	157.5	40	575
4CM	6.95				
4CB	9.86	146.9	153.0	N/A	N/A

Test 11 results.

Core No.	Void Content (%)	Dry Unit Weight (pcf)	SSD Unit Weight (pcf)	C.A. Fracture (%)	Split Tens. Strength (psi)
1AT	7.80	153.0	157.9	60	545
1AM	7.88				
1AB	7.54	148.1	152.8	60	540
1BT	7.26	152.0	156.6	50	690
1BM	7.58	148.5	153.2		
1BB	7.49	148.3	153.0	80	655
1CT	7.60	150.4	155.2	50	710
1CM	7.76				
1CB	8.68	145.3	150.7	50	630
2AT	8.46	149.2	154.5	30	675
2AM	7.80				
2AB	8.01	149.7	154.7	80	680
2BT	8.08	148.8	153.8	70	725
2BM	8.40	148.2	153.5		
2BB	8.23	149.6	154.7	70	505
2CT	7.96	149.4	154.3	N/A	N/A
2CM	8.44				
2CB	8.98	148.7	154.3	50	580
3AT	8.11	148.8	153.9	50	465
3AM	7.96				
3AB	8.64	149.5	154.9	70	515
3BT	8.47	147.8	153.1	30	465
3BM	7.74	150.3	155.2		
3BB	8.37	150.1	155.4	60	505
3CT	8.40	148.7	153.9	40	505
3CM	7.81				
3CB	8.14	145.7	150.8	60	570
4AT	6.64	150.6	154.8	60	635
4AM	7.30				
4AB	7.26	151.8	156.3	80	365
4BT	6.34	150.8	154.7	80	700
4BM	5.72	152.0	155.6		
4BB	5.22	152.5	155.8	60	695
4CT	7.61	149.5	154.2	70	635
4CM	6.40				
4CB	5.78	151.7	155.3	40	740

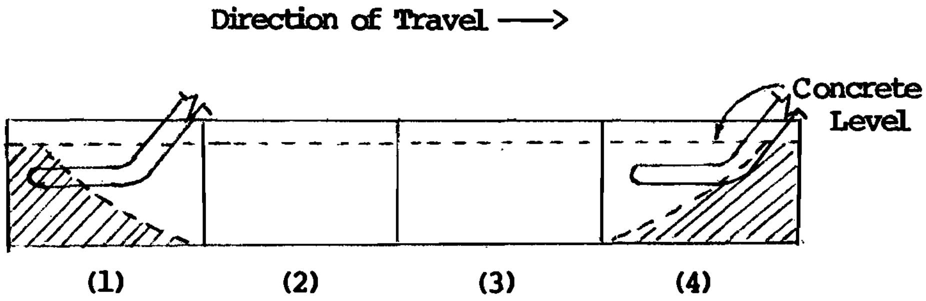
APPENDIX F

DEVELOPMENT OF FIGURES

Introduction

During the actual casting and vibration of the concrete slabs and after viewing the hardened slabs and retrieving the core samples, it was noticed that during the consolidation procedure the concrete contained in the first slab of the forms did not receive the same degree of vibration as the concrete in the following slabs. Identical problems were also encountered in the last slab of the forms. These problems could be realized best by examining what occurred as the concrete was vibrated. Figure 30 depicts the consolidation procedure.

Figure 30. The consolidation procedure.



As the tests were performed the vibrators were lowered into slab #1 and allowed to remain for a few seconds, until the concrete appeared fluid. They were then moved toward the end of the forms at a rate of about 12 to 14 fpm. When the other end of the forms was encountered, the vibrators were slowly raised from the concrete and set aside. As could be noted by the shaded regions in Figure 28, these areas were found to contain excessive honeycombing due to a lack of adequate consolidation. The problems encountered in slab #1 could be attributed to the fact that the concrete had received no initial vibration, however small it might be, from the vibrators as they approached the slab. Normally, the concrete had already undergone the initial slumping before the vibrators actually passed through. This slab, however, received no initial slumping and all of the consolidation had to occur while the vibrators were in place. It would have been impossible for this problem to be eliminated without knowing exactly how long the vibrators should remain in place in this slab to give a consolidation effort equal to that imparted on the other slabs.

The problems encountered in slab #4 were inherent to the way the test was designed. After the vibrators entered slab #4 the back of the vibrators came in contact with the back of the forms. Since the maximum forces created by the vibrator are projected only from the first half of the head (See Figure 1, p. 10) it was impossible to adequately consolidate the back portion of this slab without removing the vibrators and replacing them turned in the other direction. This problem can be associated with the problem encountered in the field as the paving machine approaches a construction joint, where the use of manually operated spud vibrators is required.

When the core samples were taken from the hardened concrete these problems became so apparent that it was soon realized that the data accumulated from batches 1 and 4 could not be used to describe the achieved consolidation. Two problems led to this conclusion. First, ASTM C642 could not be used to determine the void content or the unit weight of some of the core slices. The concrete was so honeycombed that the test would not adequately yield true SSD weights of the samples. It is also stated in ASTM C642 that test specimens must be free from observable cracks, fissures, or shattered edges, and therefore batch 1 and 4 specimens could not be tested under the terms of this standard test. This left no option but to seek another way of determining the void content of the samples. A number of methods were considered:

1. Measuring the dimensions of the samples to determine their actual volume.

2. Placing a rubber membrane around the concrete while saturated in order to make an accurate measurement of the saturated-surface dry condition.

3. Using paraffin to fill all of the voids so that the void content could be determined.

This was when the second problem had to be considered. If the void content of these poorly consolidated samples could be determined, would this yield any beneficial information relating to the consolidation of the concrete? Since the reasons for the inadequate consolidation in batches 1 and 4 had already been determined, the decision was made that the concrete contained in slabs 1 and 4 of each test did not reflect the type of information desired. The problems were deemed unavoidable, and restricting them to slabs 1 and 4 only enhanced the reliability of data retrieved from slabs 2 and 3.

Development of the Figures

While the data accumulated from slabs 1 and 4 of each test could not be used when determining the consolidation of the concrete, it was found that it could be used, in most instances, to determine the relationship of void content to splitting tensile strength. The excessively honeycombed specimens were still broken to determine their splitting tensile strength. Care was taken to place each of the core slices under the load so that they would break along a solid plane of concrete. This proved to be quite successful, and therefore reliable splitting tensile strength data was recorded in most cases. The void content of these samples had already been determined under the terms of ASTM C642 (even though the specimens did not meet the requirements of the test). Realizing that this test would not yield the actual void content of the samples, it would suffice to reveal the void content of the concrete other than the excessively large voids. Since the concrete in the plane of the splitting tensile strength fracture contained no large voids, ASTM C642 adequately determined the void content of the concrete in that plane. This was verified by plotting the data points of splitting tensile strength vs. void content for batches 1 and 4, and for batches 2 and 3 separately. The analysis of the linear regression lines through these points showed that they were extremely close to presenting the same information. Every figure of splitting tensile strength vs. void content that contains linear regression lines was, therefore, created by using data points from all of the concrete core sections in all of the slabs of each test (See Figures 13, p. 44; 15, p. 49; 16, p. 54; 17, p. 56; 18, p. 58; and 19, p. 61). The only data points that were omitted were those that were found to be irrepresentative of the vibrated concrete.

The data used to derive the mean and standard deviation values used to construct the boxes in the figures of splitting tensile strength vs. void content was taken from slabs 2 and 3 only (See Figures 13, p. 44; 15, p. 49; 16, p. 54; 17, p. 56; 18, p. 58; and 19, p. 61). This information could more accurately be used to describe the degree of consolidation attainable for a given vibratory effort. The samples taken from these slabs did not contain excessive voids, and ASTM C642 could be used to adequately determine their void content.

APPENDIX G

DATA AND STATISTICS FOR SELECTED FIGURES

Results of the linear regression analysis.

Test No.	Correlation Coefficient	Degrees of Freedom	Slope of the Reg. Line	Y-intercept of Reg. Line
1	-0.84	20	-136	1770
2	-0.80	20	-120	1630
3	-0.69	10	-148	1860
4	-0.019	8	-1.10	515
5	-0.66	19	-131	1750
6	-0.78	14	-117	1560
7	-0.83	20	-87.0	1300
8	-0.68	20	-61.3	1100
9	-0.68	18	-106	1490
10	-0.48	20	-114	1520
11	-0.46	20	-51.5	991
XT	+0.43	10	0.0713	8.25
XB	+0.096	10	0.0138	7.25

Note: Results were taken from analysis of selected data points in batches 1 through 4 of each test. Tests XT and XB denote the linear regressions for the tests that compared distance from the vibrator to void content (XT for the analysis of the top section of concrete, and XB for the analysis of the bottom).

Mean and standard deviation values for coarse aggregate fracture.

Test No.	Overall Mean (%)	Top Mean (%)	Top Std. Dev. (%)	Bottom Mean (%)	Bottom Std. Dev. (%)
1	54	35	22	73	14
2	44	32	12	57	10
3	42	32	13	52	12
4	51	44	23	60	18
5	48	42	15	58	17
6	47	30	15	63	18
7	53	38	19	67	18
8	44	27	12	62	13
9	58	37	22	78	13
10	58	40	19	77	8
11	55	44	17	65	10

Note: Results were taken from analysis of all data from batches 2 and 3 of each test.

Mean and standard deviation values for splitting tensile strength.

Test No.	Overall Mean (psi)	Top Mean (psi)	Top Std. Dev. (psi)	Bottom Mean (psi)	Bottom Std. Dev. (psi)
1	670	570	40	770	70
1A		560	40	800	55
2	630	520	30	735	40
2A		525	15	745	45
3	675	540	85	815	125
3A		515	95	875	100
4	510	490	60	530	120
4A		500	65	575	120
5	580	480	110	730	115
6	565	455	70	670	80
7	555	465	35	645	70
8	570	485	60	655	90
9	690	685	25	700	160
10	650	600	30	705	150
11	560	565	125	560	70

Note: Results were taken from analysis of all data in batches 2 and 3 of each test, except for tests 1A, 2A, 3A, and 4A. For these four tests, all core "C" data was omitted from the analysis to aid in the comparison of vibrator spacing.

Mean and standard deviation values for void content.

Test No.	Overall Mean (%)	Top Mean (%)	Top Std. Dev. (%)	Bottom Mean (%)	Bottom Std. Dev. (%)
1	8.36	8.78	0.19	7.54	0.29
1A		8.76	0.17	7.49	0.36
2	8.43	9.07	0.34	7.33	0.37
2A		9.17	0.40	7.36	0.47
3	8.29	8.69	0.46	7.31	0.33
3A		8.74	0.56	7.28	0.33
4	7.04	7.97	0.99	5.85	1.22
4A		8.33	1.18	6.49	1.17
5	8.74	9.38	0.29	7.92	0.31
6	8.77	9.44	0.58	7.87	0.55
7	8.79	9.51	0.19	7.72	0.30
8	9.00	9.82	0.21	7.77	0.26
9	7.34	7.86	0.18	6.45	1.31
10	7.25	7.73	0.53	7.29	0.50
11	8.22	8.25	0.22	8.40	0.36

Note: Results were taken from analysis of all data in batches 2 and 3 of each test, except for tests 1A, 2A, 3A, and 4A. For these four tests, all core "C" data was omitted from the analysis to aid in the comparison of vibrator spacing.

APPENDIX H

VIBRATOR MONITORING SYSTEM

The Vibrator Monitoring System (VMS) was developed to detect and indicate the failure of one or more concrete vibrators. A specially designed sensor is attached to each vibrator on the paving machine. The sensor contains a hermetically sealed reed switch which is normally open. As the vibrator is operating, the reed switch is set into oscillation, alternately closing and opening the contacts at the rate of the vibrator. The sensor output signals are sent to the main control unit via shielded cables.

The control unit, shown in Figure H1 contains the detector circuit board, power supply,indicator lamps and the audio alarm. The circuit board contains fifteen comparator circuits, one for each vibrator sensor. A group of four typical circuits are shown and each circuit is identical, using an operational amplifier as a comparator to compare the rectified and smoothed sensor pulses to a reference voltage. If all sensor contacts are vibrating open and closed, the voltage to the negative input of the comparator will be high producing a zero output keeping the indicator lamps and alarm off. If a vibrator should quit the respective input voltage to the comparator be zero. The level is less than the reference voltage producing a positive voltage output. This voltage turns on the associated transistor, illuminating the lamp. The positive signal is also sent to the audio alarm through the "or" network. Thus, if any vibrator stops operating, the audio alarm will sound and a light or lights on the control unit indicates the defective unit or units. Also, while the concrete is being liquified the audio alarm is activated periodically until complete liquifaction has been obtained.

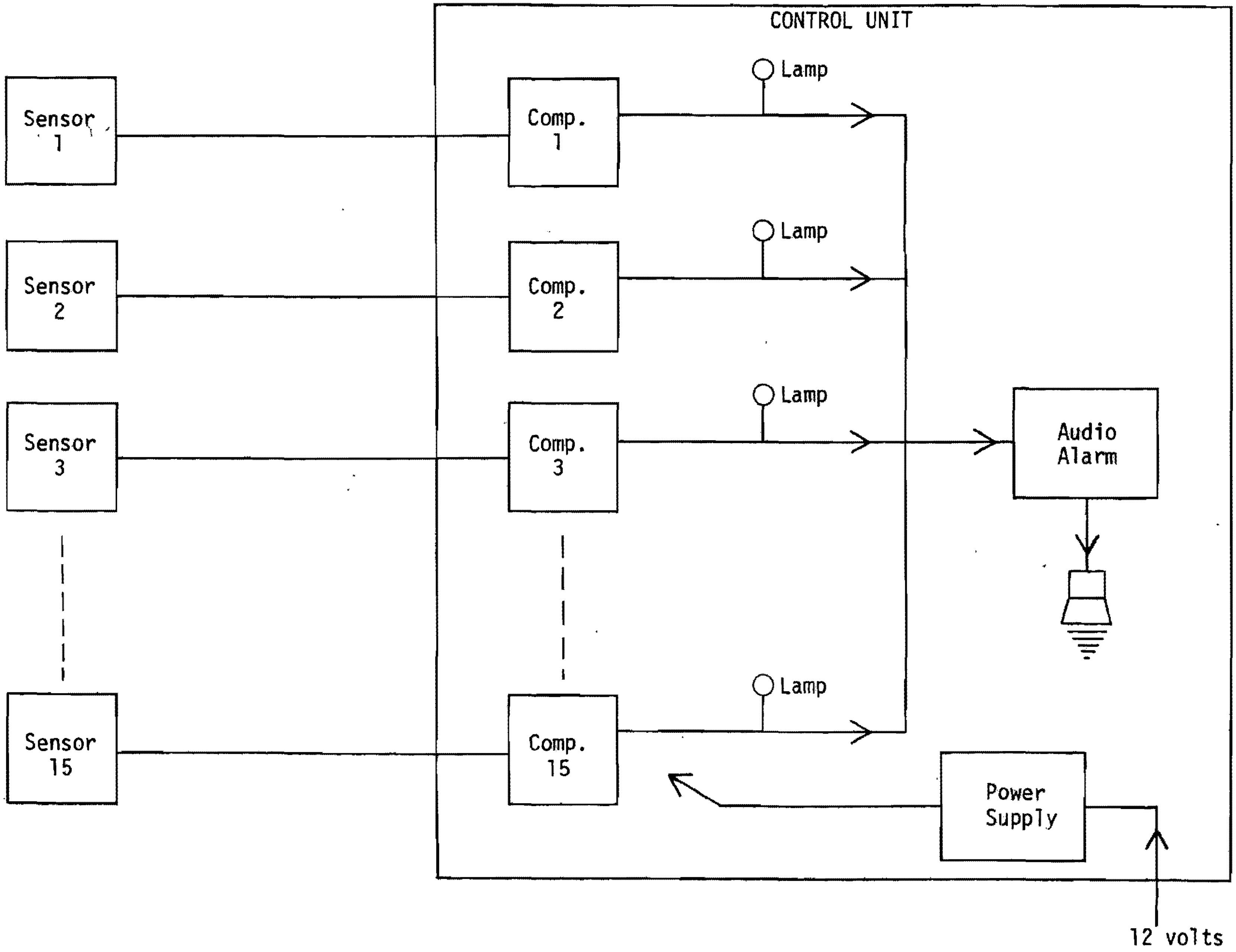
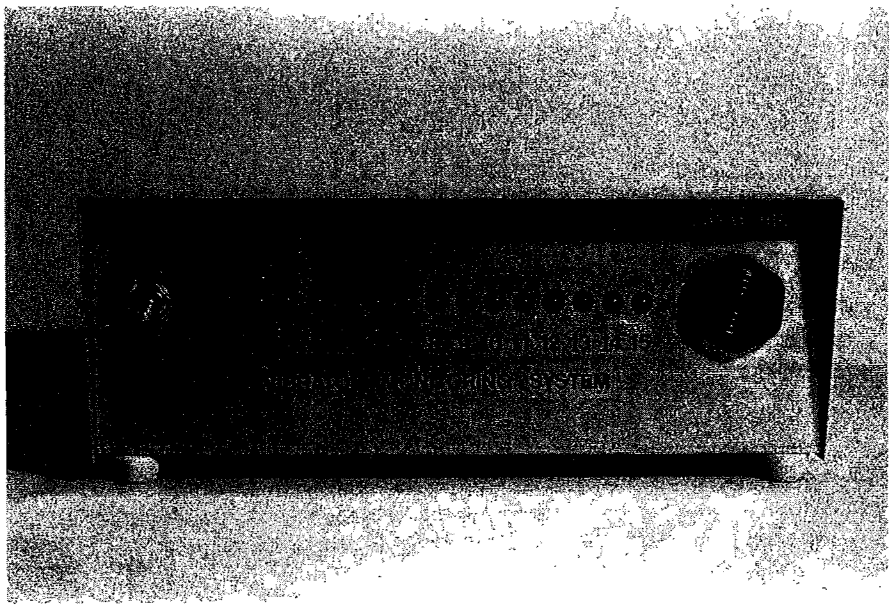
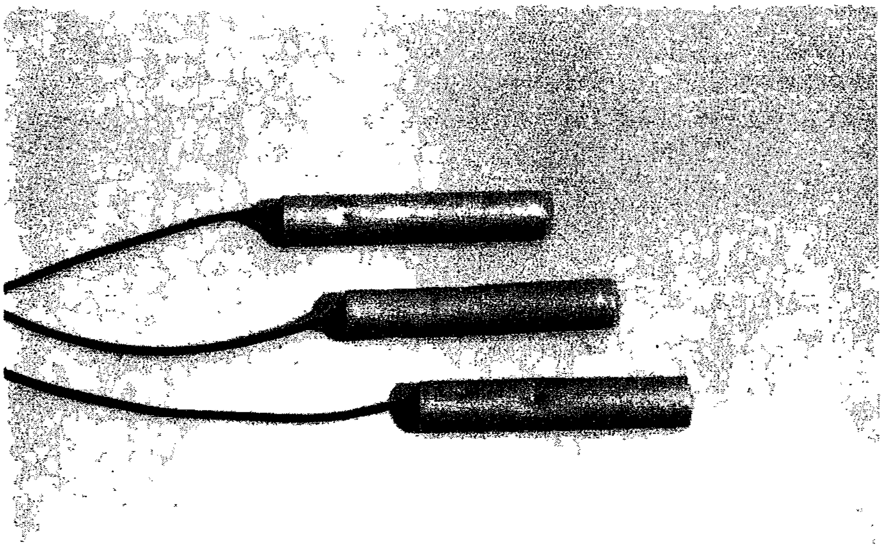


Figure 32. Schmetic Diagram of the VMS Control Unit.



a. Control Unit



b. Sensors

Figure 33. VMS Control Unit and Sensors.