TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
Physical Research No. 53

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Effect of Internal Vibration of
Portland Cement Concrete During Paving

5. Report Date
March, 1974

6. Performing Organization Code

7. Author(s)
Robert P. Elliott

8. Performing Organization Report No.
Physical Research No. 53

9. Performing Organization Name and Address
Bureau of Materials & Physical Research
Physical Research Group
2300 Dirksen Parkway
Springfield, Illinois 62764

10. Work Unit No.

11. Contract or Grant No.
IHR-503

12. Sponsoring Agency Name and Address
Illinois Department of Transportation
Bureau of Materials and Physical Research
2300 Dirksen Parkway
Springfield, Illinois 62764

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Study conducted as a part of FHWA National Experimental and Evaluation Program, "Proper Vibration of PCC Pavements"

16. Abstract

To determine the effects of internal vibration on the properties of portland cement concrete pavement, a field experiment was conducted in which the vibrator frequency, vibrator eccentric size, and paver speed were varied. Subsequently, samples of the hardened concrete were removed from the test locations and laboratory measures of strength, density, air content, and segregation were made. The results were then compared to the test variations, the slump and air content of the plastic concrete, and the concrete surcharge height above the vibrators.

Within the range tested, vibrator eccentric size was found to have the strongest influence on the concrete properties and paver speed the weakest. Nevertheless, none of the combination of variations produced unacceptable results. Of prime immediate significance was the field observation that paver speed and vibrator frequency can be controlled so that adequate consolidation and a good surface behind the paver are obtained without accumulating foam or excess mortar ahead of the paver.

17. Key Words
Concrete Consolidation, Internal Vibration, Strength, Density, Air Content, Segregation, Paver Speed

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
44

22. Price

Form DOT F 1700.7 (8-69)

State of Illinois
DEPARTMENT OF TRANSPORTATION
Bureau of Materials and Physical Research

EFFECT OF INTERNAL VIBRATION OF PORTLAND CEMENT CONCRETE DURING PAVING

by
Robert P. Elliott

Final Report of
Research Project IHR-503

A Research Study
by
Illinois Department of Transportation
Bureau of Materials and Physical Research
Physical Research Group

March, 1974

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EFFECT OF INTERNAL VIBRATION OF PORTLAND CEMENT CONCRETE DURING PAVING

INTRODUCTION

The importance of consolidation and the beneficial effects of vibration in obtaining quality concrete products have been thoroughly documented. However, in recent years with the advent of slipform paving, high production rates, and the increased use of Continuously Reinforced Concrete Pavement, it has become obvious that more definitive information is needed to quantify the effects of vibration and to permit the development of realistic construction control specifications. This need is evidenced by the occurrence of isolated pavement failures related to inadequate concrete consolidation and the appearance of surface defects that result from incorporating into the pavements foam-like materials that have been generated by high vibration intensities.

As an initial attempt at determining the effects of the major vibrational parameters, the Illinois Department of Transportation conducted a small study in conjunction with the Federal Highway Administration's National Experimental and Evaluation Program entitled "Proper Vibration of PCC Pavements." This Federal program involved several states, each conducting similar small scale studies. While as a whole, the program may be able to quantify to some extent the effects of the paramters studied, the individual state studies were sufficient only to qualify the general effects of these parameters and to serve as guides for future research in the area. This report covers only the efforts and findings of the Illinois Department of Transportation as a participant in the Federal program.

FIELD PROGRAM

The program was established as a field experiment to be conducted on a regular contract paving project. For the Illinois portion of the program a site near

Mahomet, Illinois was selected (Figure 1). This job was chosen on the basis of the pavement type (CRCP) and paving equipment (Rex Slipform) being representative of that commonly used in the state and on the contractor's (General Paving Company) willingness to cooperate in the experiment.

During the study, three factors related to the intensity of vibrational input to the concrete were varied: (1) vibrator frequency, (2) vibrator eccentric size, and (3) speed of the paver. A fourth factor included in the Federal program, but not included in the Illinois portion, was vibrator spacing.

In addition to these controlled variables, the following three items were measured at each test location: (1) concrete slump, (2) concrete air content, and (3) height of the concrete surcharge over the vibrators.

The plan for the field phase of the study was established on the basis of collecting as much data as possible with only minimal interference to the contractor's normal operations. This was considered necessary to avoid force account charges for extra work since the selected project was under contract when the study was conceived, and, therefore, did not include provisions for the experiment. For this reason, laboratory tests were substituted for certain field tests that the FHWA had suggested be performed behind the paver and the factors varied in the test were totally controlled only over the test locations. In some cases where low vibrational intensities and high paver speeds were found to be creating finishing problems behind the paver, the length of complete control was less than ten feet. This is believed to have masked some of the influence of these variables on the test results.

The experiment was designed as a 3x3x3 factorial with one replication. Three vibrator eccentrics of 1 5/8-inch, 1 3/4-inch, and 1 7/8-inch nominal size were employed. Each size was used for an entire day, with the eccentrics in only the driving lane side of the paver being changed. The 1 7/8-inch eccentrics normally used by the contractor were used in the passing lane throughout the test.

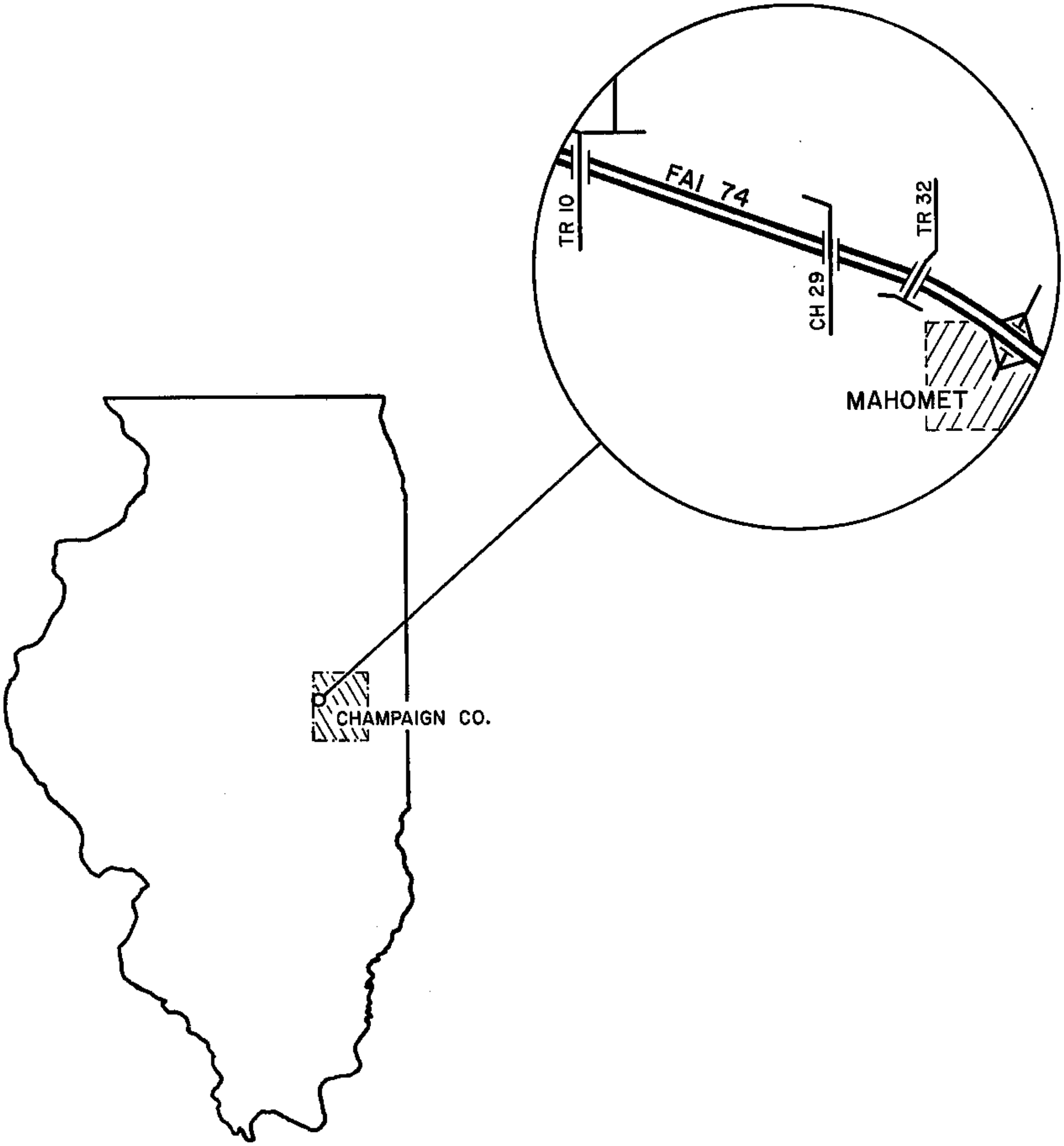

FIGURE I. GENERAL LOCATION OF TEST SITE

With each size eccentric, nominal paver speeds of 6 feet per minute, 8.5 feet per minute, and 12 feet per minute, and nominal vibrator frequencies in the concrete of 7,200 rpm, 8,600 rpm, and 10,000 rpm were used. The actual paver speeds and frequencies, which varied somewhat from the nominal values, were measured during the tests and were used where possible in the data analyses. In addition to these measurements, concrete slump and air contents were taken just ahead of the paver from the concrete placed at each test site. As mentioned previously, no field tests were conducted on the concrete behind the paver.

Field tests were conducted at a total of 107 locations. Of these, 54 were later selected for pavement coring and laboratory testing. The selection was made on the basis of completing the factorial design and restricting, as far as possible, the variability of the concrete. Nevertheless, the concrete slump at the locations used varied from 1 1/4 to 3 1/8 inches and the air content of the fresh concrete ranged from 4.4 to 6.7 percent. This degree of variability was due to the unfortunate necessity of conducting the experiment during marginal weather conditions late in the construction season when mix control often proves to be more difficult.

LABORATORY PROGRAM

In the laboratory phase, four concrete properties were tested: (1) strength, (2) density, (3) air content, and (4) segregation. For testing, two 4-inch diameter and two 2-inch diameter concrete cores were removed from each selected location. One core of each size was taken in the path of a vibrator and one of each size from midway between vibrators. Figure 2 shows the vibrator spacings and the sample locations relative to the vibrator paths.

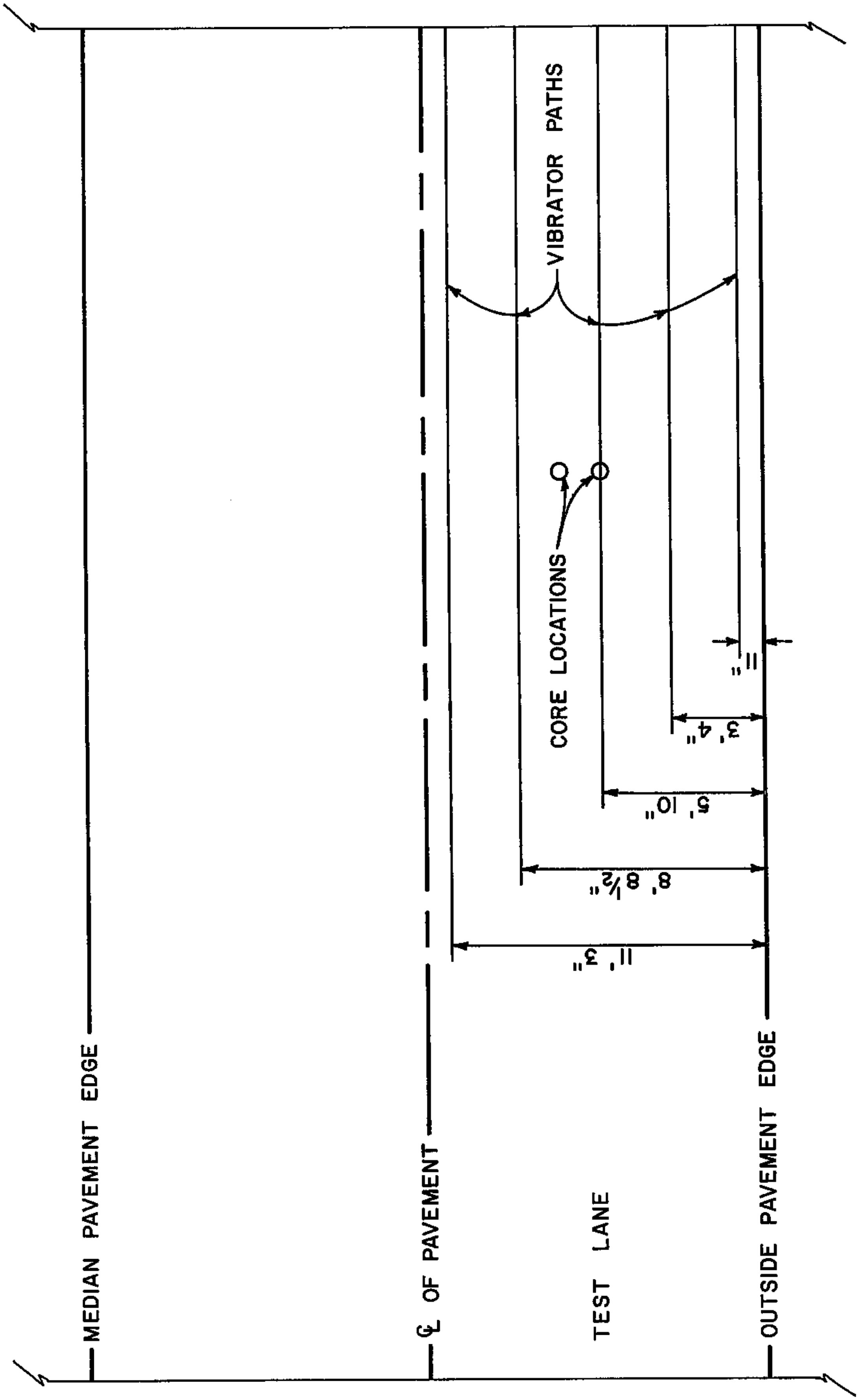

FIGURE 2. VIBRATOR SPACING AND CORE LOCATIONS RELATIVE TO PAVEMENT EDGE

The strength of the concrete was measured in two ways. In accordance with the FHWA program guidelines, Swiss Hammer readings were taken at the top, upper third point, center, and lower third point of the 4-inch cores. These readings were not included in the Illinois data analyses but were reported to FHWA to fulfill the NEEP data requirements. Also, compressive strength tests were made on the 2-inch cores. These cores were separated into upper and lower halves and each half was tested in accordance with test method ASTM-39. At the time of testing the concrete cores were 5 months old.

Density measurements were made on the upper and lower halves of the 4-inch concrete cores in accordance with test method ASTM C-642. Air content of the hardened cores was determined using the Illinois high-pressure air meter. These tests also were performed on the upper and lower halves of the 4-inch cores.

For the purposes of the study, a segregation test was devised. As a measure of segregation, the FHWA guidelines suggested sampling the concrete just behind the paver and conducting sieve analyses on the aggregate recovered from the upper and lower portions of the sample. Since refilling and finishing of these sample locations would create extra work for the contractor, a substitute measure was developed which could be made on the hardened concrete cores. This involved the measurement of the length of coarse aggregate particles that fell on lines scribed across the face of a split concrete core. After the air and density tests had been made, the 4-inch cores were split lengthwise. Lines 3 3/4 inches long were subsequently scribed 1/2 inch up from the bottom and 1/2 inch down from the top. The length of coarse aggregate particles falling on these lines were then measured. The ratio of the upper to lower total measured lengths was defined as core's Segregation Index. Ideally, with no segregation this value would be 1.0. Extreme variation from 1.0 would indicate the presence of segregation. While considerable variation was expected between the Segregation Indexes of individual core samples, the combination of all 54 measures was expected to provide an indication of segregation effects.

DATA ANALYSES

The preliminary step in analyzing the various data was to plot each data point on graphs versus two vibration intensity parameters. The first of these was a force parameter which was defined as the hypothetical centrifugal force generated by the vibrator at zero amplitude. The equation for this parameter is:

$$F = m\ r\ \omega^2$$

in which

F = centrifugal force

m = mass of the vibrator eccentric

r = distance from center of gravity of the eccentric to axis of rotation

ω = vibrator frequency

The second parameter was called the vibration index (VI) and was defined as the product of the force and the reciprocal of the paver speed (v). That is:

$$VI = F/v$$

These parameters were selected because they incorporated all three of the factors controlled during the test--eccentric size, vibrator frequency, and paver speed.

In addition, analysis of variance and correlation and regression techniques were employed to determine significant relationships between the data and the various factors controlled or measured.

For the analyses of variance, the data were categorized according to the nominal values of the three controlled parameters. Actual measured values of both the controlled and uncontrolled factors were used in the correlation and regression computations.

Compressive Strength

Figure 3 is the plot of compressive strength versus the force parameter for the bottom halves of cores taken between the vibrators. This plot is typical of the compressive strength versus force or vibration index graphs in that the points appear to be randomly distributed with no indication of a relationship.

The compressive strength analysis of variance results are displayed in Tables 1 and 2. These indicate a significant effect in only one instance--the effect of eccentric size on the compressive strength of the bottom half of cores from the vibrator path. A check of the data revealed that for these core halves the average compressive strength was highest for the 1 3/4-inch (middle size) eccentric.

Linear correlation coefficients between compressive strength and the factors measured in the field are shown in Table 3. Of these only the negative correlation between paver speed and the compressive strength of the top half of cores from the vibrator path is significantly greater than zero, indicating a trend of higher compressive strength with slower paver speeds.

In addition, an evaluation of the strength data revealed that the upper half of the cores from between vibrators had a significantly lower average than the average strength of the other core halves. This suggests that vibrator spacing, a variable not included in the test, could have a significant effect on concrete

TABLE 1
Analysis of Variance of
Compressive Strength of Cores from the Vibrator Path

Source	df	Sum of Squares	Mean Square	F
TOP HALF OF CORES				
Frequency - ω	2	1,634,614	817,307	0.55
Eccentric Size - E	2	1,591,406	795,703	0.54
Paver Speed - v	2	5,016,188	2,508,094	1.70
ωE	4	6,876,268	1,719,067	1.16
ωv	4	3,453,742	863,436	0.58
Ev	4	5,362,700	1,340,675	0.91
ωEv	8	5,578,136	697,267	0.47
Error	27	39,876,612	1,476,912	
Total	53	69,389,584		
BOTTOM HALF OF CORES				
Frequency - ω	2	274,044	137,022	0.17
Eccentric Size - E	2	6,464,881	3,232,440	4.05**
Paver Speed - v	2	1,997,934	998,967	1.25
ωE	4	5,131,919	1,282,979	1.61
ωv	4	3,307,683	826,921	1.04
Ev	4	2,343,489	585,871	0.73
ωEv	8	6,235,376	779,422	0.98
Error	27	21,544,803	797,956	
Total	53	47,300,032		

* Indicates significance at the 90% level
** Indicates significance at the 95% level
*** Indicates significance at the 99% level

TABLE 2
Analysis of Variance of
Compressive Strength of Cores from Between Vibrators

Source	df	Sum of Squares	Mean Square	F
TOP HALF OF CORES				
Frequency - ω	2	255,703	127,851	0.13
Eccentric Size - E	2	3,364,454	1,682,227	1.65
Paver Speed - v	2	1,610,572	805,286	0.79
ωE	4	1,322,189	330,547	0.32
ωv	4	4,361,596	1,090,399	1.07
Ev	4	4,179,423	1,044,856	1.02
ωEv	8	9,686,669	1,210,833	1.19
Error	27	27,575,267	1,021,306	
Total	53	52,355,776		
BOTTOM HALF OF CORES				
Frequency - ω	2	2,379,630	1,189,815	1.26
Eccentric Size - E	2	925,093	462,546	0.49
Paver Speed - v	2	733,880	366,940	0.39
ωE	4	7,891,168	1,972,792	2.09
ωv	4	524,508	131,127	0.14
Ev	4	834,971	208,743	0.22
ωEv	8	2,535,937	316,992	0.34
Error	27	25,525,950	945,406	
Total	53	41,351,056		

* Indicates significance at the 90% level
** Indicates significance at the 95% level
*** Indicates significance at the 99% level

TABLE 3
Correlation Coefficients With Core Compressive Strengths

Variable	TOP HALF OF CORES		BOTTOM HALF OF CORES	
	Vibrator Path	Between Vibrators	Vibrator Path	Between Vibrators
Slump	0.000	-0.003	-0.129	-0.152
Paver Speed	-0.280*	-0.184	0.016	0.099
Head	-0.101	-0.058	0.071	0.141
Eccentric Size	0.007	-0.062	0.039	0.108
Frequency	-0.104	0.020	0.007	0.078

* Indicates significance at the 95% level
** Indicates significance at the 99% level

strength and that the spacing should be somewhat less than was employed during this test. The average core strengths by location are shown below.

CORE LOCATION

	Vibrator Path	Between Vibrations
Top Half	5204	4774
Bottom Half	5521	5379

Density

Figures 4 through 7 show core density plotted against the force parameter for the top and bottom halves of the cores from the vibrator path, and the top and bottom halves of the cores from between vibrators. A definite trend of increased density with increased force is shown in the plot for the bottom halves of cores from the vibrator path. Somewhat lesser trends are also apparent for the top halves of those cores and the bottom halves of the cores from between vibrators. Little or no increase is apparent for the top of cores from between vibrators.

Figure 8 displays regression lines that were fitted to the data shown in Figures 4 through 7. These indicate that the highest density and strongest relationship with the force parameter was found in the lower halves of the cores from the vibrator path and that, in general, lower densities were achieved between the vibrators.

Similar plots were made using the vibration index in place of the force parameter. While somewhat similar trends were noted, the data scatter was greater, suggesting that paver speed did not influence the density of the concrete.

Table 4 displays the results of analyses of variance on the data from the vibrator path. In each case, the size of the eccentric is shown to have a highly significant influence on the density. Vibrator frequency also is shown to significantly influence the density of the bottom halves of the cores.

TABLE 4
Analysis of Variance of
Density of Cores from the Vibrator Path

Source	df	Sum of Squares	Mean Square	F
TOP HALF OF CORES				
Frequency - ω	2	0.00068	0.00034	0.35
Eccentric Size - E	2	0.01330	0.00665	6.93***
Paver Speed - v	2	0.00023	0.00012	0.13
ωE	4	0.00289	0.00072	0.75
ωv	4	0.00169	0.00042	0.43
Ev	4	0.00193	0.00048	0.50
ωEv	8	0.00898	0.00112	1.17
Error	27	0.02605	0.00096	
Total	53	0.05575		
WHOLE CORES				
Frequency - ω	2	0.00390	0.00195	3.75**
Eccentric Size	2	0.00668	0.00334	6.43***
Paver Speed - v	2	0.00014	0.00007	0.13
ωE	4	0.00196	0.00049	0.94
ωv	4	0.00286	0.00071	1.36
Ev	4	0.00351	0.00088	1.69
ωEv	8	0.00389	0.00049	0.94
Error	27	0.01402	0.00052	
Total	53	0.03693		
BOTTOM HALF OF CORES				
Frequency - ω	2	0.01441	0.00721	21.2***
Eccentric Size - E	2	0.00611	0.00306	9.00***
Paver Speed - v	2	0.00063	0.00031	0.91
ωE	4	0.00145	0.00036	1.06
ωv	4	0.00141	0.00031	0.91
Ev	4	0.00121	0.00035	1.03
ωEv	8	0.00356	0.00044	1.29
Error	27	0.00910	0.00034	
Total	53	0.03788		

* Indicates significance at the 90% level
** Indicates significance at the 95% level
*** Indicates significance at the 99% level

Analyses of variance of the data from between vibrators (Table 5) again shows eccentric size to be the significant factor. Interaction between frequency and eccentric size is shown to be significant in two cases. In one case, interaction between frequency and paver speeds is significant. With this one exception of interaction, paver speed was not found to be a significant factor.

Table 6 is a listing of correlation coefficients between the measured densities and the various factors controlled or measured during the field phase. This shows density to have a strong positive correlation with eccentric size for all sample locations and with frequency for the bottom halves of the cores in the vibrator paths. Particularly interesting, however, are the correlation coefficients with slump.

Intuitively, increasing the slump of a mix could have either of two effects on the density -- (1) an increase (positive correlation) due to a reduction in the effort required for consolidation; or (2) a decrease (negative correlation) due to the added water becoming excess moisture in the consolidated concrete mass. The effect that would occur in a given situation depends on the range of slump being dealt with, the workability of the mix, and the degree of consolidation effort being employed. In general, a negative correlation or decreased density could be anticipated for the concrete from areas close to a vibrator and a positive correlation or increased density for the concrete from areas some distance away where the vibrator's effectiveness would be diminished.

In this study, the correlation coefficients for cores from the vibrator path were not significant, suggesting that either the two effects balanced one another or that the excess moisture at the higher slumps was removed by the intensity of the vibrators. At the same time, a strong negative correlation was found for the cores from between the vibrators. This indicates the presence of excess moisture

TABLE 5
Analysis of Variance of
Density of Cores From Between Vibrators

Source	df	Sum of Squares	Mean Square	F
		TOP HALF OF CORES		
Frequency - ω	2	0.00051	0.00026	0.71
Eccentric Size - E	2	0.00188	0.00094	2.54*
Paver Speed - v	2	0.00010	0.00005	0.14
ωE	4	0.00560	0.00140	3.79**
ωv	4	0.00097	0.00024	0.65
Ev	4	0.00097	0.00024	0.65
ωEv	8	0.00438	0.00055	1.49
Error	27	0.01005	0.00037	
Total	53	0.02448		
		WHOLE CORES		
Frequency - ω	2	0.00043	0.00022	0.24
Eccentric Size - E	2	0.00563	0.00282	3.10*
Paver Speed - v	2	0.00253	0.00127	1.40
ωE	4	0.00663	0.00166	1.83
ωv	4	0.00953	0.00238	2.62*
Ev	4	0.00253	0.00063	0.69
ωEv	8	0.00753	0.00094	1.03
Error	27	0.02469	0.00091	
Total	53	0.05953		
		BOTTOM HALF OF CORES		
Frequency - ω	2	0.00073	0.00036	1.09
Eccentric Size - E	2	0.00819	0.00410	12.4 ***
Paver Speed - v	2	0.00023	0.00011	0.33
ωE	4	0.00405	0.00101	3.06**
ωv	4	0.00239	0.00060	1.82
Ev	4	0.00112	0.00028	0.85
ωEv	8	0.00347	0.00043	1.30
Error	27	0.00899	0.00033	
Total	53	0.02917		

* Indicates significance at the 90% level
** Indicates significance at the 95% level
*** Indicates significance at the 99% level

TABLE 6
Correlation Coefficients with Core Density

Variable	TOP HALF OF CORES		BOTTOM HALF OF CORES	
	Vibrator Path	Between Paths	Vibrator Path	Between Paths
Slump	-.184	-.335**	.049	-.241*
Speed	-.012	-.006	-.002	.094
Head	-.091	.053	.032	.081
Eccentric Size	.488**	.276*	.380**	.529**
Frequency	-.174	-.110	.571**	-.038

* Indicates significance at the 95% level
** Indicates significance at the 99% level

and shows that the higher slumps did not aid in the consolidation effort. In this respect, it is concluded that for uniform density the concrete slump should be maintained toward the lower end of the range used in this test.

In evaluating the density results, it should be kept in mind that both the loss of air content and segregation influence density. While both of these factors have been evaluated in the study, no attempt has been made to account for their influence in the density analyses.

Air Content

The air contents of the pavement cores were determined on the top and bottom halves of the 4-inch cores using the Illinois high-pressure air meter. This device, which utilizes a test pressure of 5,000 psi, is used in Illinois for routine testing of concrete cores. Its development is reported in Volume 35 of the Highway Research Board Proceedings.

Figure 9 displays the results of tests conducted to check the calibration of the high-pressure air meter. The plastic concrete air contents were determined using a conventional air meter. Concrete beams were then made using a consolidation effort equivalent to that used in the conventional air tests. After curing, cores were removed from the beams and tested in the high-pressure air meter. Analysis of these results indicates that on the average the air content determined by the high-pressure air meter is 0.3 percent higher than the air content measured on the plastic concrete, with a standard error of 0.44 percent. This demonstrates that while the device is sufficiently accurate for routine testing, small individual differences between plastic and hardened air contents should not be compared. Nevertheless, trends developed from a number of tests should be meaningful.

Comparison of the plastic and hardened air contents of all the cores is shown in Figure 10. In this figure the hardened air content represents the average value of the top and bottom core halves. This figure indicates that between vibrators the air content remained relatively constant during the paving operation but that in the vibrator paths some air was lost. The average loss was approximately 1 1/2 percent.

Figure 11 is a plot of the air content loss of the top half of the cores from the vibrator path versus the force parameter. As used here, air content loss is defined as the difference between plastic and hardened air contents. While this indicates a loss of air content throughout, there appears to be a general trend of greater loss at higher force values. A similar plot using the vibration index as the abscissa did not show this trend, suggesting that, within the range tested, paver speed did not influence the amount of air loss.

Table 7 contains the results of analyses of variance relative to differences between the plastic air contents and hardened air contents. These indicate that in the vibrator path, only vibrator frequency had a significant effect on the loss of air content and that between vibrators, air content was affected by an interaction between frequency and eccentric size.

Correlation coefficients between air content loss and the various parameters measured in the test are displayed in Table 8. None of the test parameters are shown to affect the air content between the vibrators. In the vibrator path, however, slump, frequency, and eccentric size are all shown to have some influence with frequency being highly significant. As in the density analyses, the correlation with slump indicates that the higher slumps could be detrimental to the concrete in that they promoted loss in air content.

Segregation

Prior to testing, all of the cores were examined for visual evidence of segregation. While some possible evidence of segregation was observed in four

TABLE 7
ANALYSIS OF VARIANCE OF AIR LOSS

Source	df	Sum of Squares	Mean Square	F
		TOP OF CORE IN VIBRATOR PATH		
Frequency - ω	2	4.37564	2.18782	2.94*
Eccentric Size - E	2	3.35286	1.67643	2.25
Paver Speed - v	2	1.69231	0.84615	1.14
ωE	4	1.31074	0.32768	.44
ωv	4	1.74796	0.43699	.59
Ev	4	2.01740	0.50435	.68
ωEv	8	0.95814	0.11977	.16
Error	27	20.07615	0.74356	
Total	53	35.53116		
		WHOLE CORE IN VIBRATOR PATH		
Frequency - ω	2	3.90064	1.95032	2.92*
Eccentric Size - E	2	1.03231	0.51616	.77
Paver Speed - v	2	0.80953	0.40477	.61
ωE	4	0.71213	0.17803	.27
ωv	4	0.30241	0.07560	.11
Ev	4	1.12157	0.28039	.42
ωEv	8	1.20148	0.15018	.22
Error	27	18.03242	0.66787	
Total	53	27.11246		
		WHOLE CORE BETWEEN VIBRATORS		
Frequency - ω	2	0.02926	0.01463	.05
Eccentric Size - E	2	0.18454	0.09227	.33
Paver Speed - v	2	0.58815	0.29407	1.05
ωE	4	3.02268	0.75567	2.71*
ωv	4	0.83074	0.20768	.74
Ev	4	1.05796	0.26449	.95
ωEv	8	2.40147	0.30018	1.08
Error	27	7.52872	0.27884	
Total	53	15.64352		

* Indicates significance at the 90% level
** Indicates significance at the 95% level
*** Indicates significance at the 99% level

TABLE 8

Correlation Coefficients with Air Loss

	WHOLE CORES		TOP OF CORES
	Vibrator Path	Between Paths	Vibrator Path
Slump	.272*	-.095	.313*
Speed	-.043	.029	-.072
Head	.024	-.165	.023
Eccentric Size	.238**	.123	.165
Frequency	.680**	.013	.555**

* Indicates significance at the 95% level

** Indicates significance at the 99% level

cores, no severe segregation was apparent. In this respect, segregation does not appear to be a significant problem within the range of vibration employed in the test. Nevertheless, it was recognized that segregation occurs over a continuous spectrum ranging from none to complete separation of the concrete components. Consequently, even though not readily apparent to visual observation, subtle variations in the distribution of coarse aggregate could be present, indicating minor degrees of segregation. To measure and quantify these variations, the Segregation Index (SI) was determined for each core.

As described earlier, SI was defined as the ratio of the measured lengths of coarse aggregate particles falling on lines scribed at the top and bottom of the face of the split halves of the 4-inch cores. This index can be defined by the equation:

$$SI = \frac{L_t}{L_b}$$

in which

L_t = total measured length of coarse aggregate particles on a 3 3/4-inch line scribed 1/2 inch from top of the core

L_b = total measured length of coarse aggregate particles on a 3 3/4-inch line scribed 1/2 inch from the bottom of the core

With the random nature of aggregate distribution, considerable variation was expected in the SI values which would obscure the meaning of individual SI's. Nevertheless, trends developed from the data were expected to yield some information relative to the influence of the test parameters on concrete segregation.

In this respect, the smaller SI values become meaningful when considered relative to the largest SI values measured. In the complete absence of segregation, the logarithm of SI would be expected to be randomly distributed in an approximately normal fashion with a mean value of zero (SI=1.0). Consequently, the probability of the occurrence of any SI value greater than 1.0 should be the same as the probability of the occurrence of its reciprocal. Assuming that the coarse aggregate particles tend to settle when segregation occurs, the smaller SI values would indicate segregation. On this basis, SI values smaller than the reciprocal of the highest SI's measured would be an indication of segregation.

Of the 108 SI's measured, only four exceeded 2.0, with the highest value being 3.38. From the above discussion, these values suggest that segregation can be suspected for SI's less than 0.5 (the reciprocal of 2) and that segregation is likely if the SI is less than 0.3 (the reciprocal of 3.38).

Figure 12 is a plot of SI versus the force parameter for cores from the vibrator path. This figure indicates a general trend of lower SI as the force increases with values less than 0.3 appearing when the force exceeds 1,000 to 1,100. On the basis of the above disucssion, this seems to indicate that segregation is beginning to develop when the force exceeds about 1,050.

Analyses of variance results are contained in Table 9. These indicate that in the vibrator path, frequency is a highly significant factor and that between vibrators, paver speed has a significant influence on the development of segregation.

Correlation coefficients between SI and the parameters measured in the test are displayed in Table 10. Again, vibrator frequency is shown to be a significant variable in the vibrator path, with paver speed significant between the vibrators.

CONCLUSION

The factors found to significantly influence concrete properties and the nature of their influence are summarized in Table 11. This shows that of the vibration parameters controlled during the test, eccentric size was found to have the strongest influence on the properties of the hardened concrete. This influence was particularly noticeable with respect to concrete density in which

TABLE 9
Analysis of Variance of
Segregation Index

Source	df	Sum of Squares	Mean Square	F
		VIBRATOR PATH		
Frequency - ω	2	1.84561	0.92281	5.79***
Eccentric Size - E	2	0.12674	0.06337	0.40
Paver Speed - v	2	0.74740	0.37370	2.34
ωE	4	0.85146	0.21287	1.34
ωv	4	1.03896	0.25974	1.63
Ev	4	0.17687	0.04422	0.28
ωEv	8	2.26965	0.28371	1.78
Error	27	4.30364	0.15939	
Total	53	11.36033		
		BETWEEN VIBRATORS		
Frequency - ω	2	.86258	0.43129	1.15
Eccentric Size - E	2	.07554	0.03777	.10
Paver Speed - v	2	3.08823	1.54412	4.12**
ωE	4	1.64171	0.41043	1.10
ωv	4	0.41302	0.10326	.28
Ev	4	0.64795	0.16199	.43
ωEv	8	3.21298	0.40162	1.07
Error	27	10.12024	0.37482	
Total	53	20.06226		

* Indicates significance at the 90% level
** Indicates significance at the 95% level
*** Indicates significance at the 99% level

TABLE 10
Correlation Coefficients with Segregation Index

	In Vibrator Path	Between Vibrators
Slump	-.091	-.018
Speed	.190	.349**
Head	-.006	.041
Eccentric Size	.095	.056
Frequency	-.335**	-.207

* Indicates significance at the 95% level
** Indicates significance at the 99% level

TABLE 11
Summary of Significant Individual Effects
Found in the Study

Variable Change	Location	
	Vibrator Path	Between Vibrators
Greater Slump	Increased air loss	Reduced density
Higher Paver Speed	Lowered strength of top half	Reduced segregation development
Larger Eccentric	Increased density Increased air loss (Highest strength in bottom half with middle size, 1 3/4," eccentric)	Increased density
Higher Frequency	Increased density in bottom half Increased air loss Increased segregation development	

eccentric size was found to be a statistically significant variable in each of the four sample locations--top and bottom cores from both in and between vibrator paths. In this respect, the largest eccentric used (1 7/8 inch) would appear to be the best for obtaining adequate, uniform consolidation.

Vibrator frequency, while not found significant as frequently as eccentric size, was also found to affect the concrete properties. While some significance was noted with respect to density, frequency primarily affected loss of air content and segregation of the concrete in the vibrator path. This suggests that a maximum frequency should be established to prevent segregation and limit the loss of air in the pavement surface.

The earlier discussion of SI and the data shown on Figure 12 indicated that segregation began to occur when the force parameter exceeded about 1,050. The average amount of air loss was also somewhat greater above this value (Figure 11). The vibrator frequency corresponding to this force when using a 1 7/8-inch eccentric is about 8,300 revolutions per minute. This suggests that for the equipment and concrete involved in the test, the optimal vibration intensity would be achieved with a 1 7/8-inch eccentric and 8,300 rpm vibrator frequency (submerged).

Paver speed, within the range tested, was found to have little effect on the hardened concrete properties since it was statistically significant only for the compressive strength of the top half of cores from the vibrator path and for segregation in cores taken between vibrators. However, some of the influence of this variable is believed to have been hidden by the fact that paver speed was controlled only immediately over the test locations. In some instances this involved less than ten feet of pavement.

During the field phase of the study, observation of the concrete both at the vibrators and just behind the paver indicated that paver speed, vibrator frequency, and eccentric size all affected both the finished appearance of the slab and the amount of mortar and foam accumulating in the roll of concrete ahead of the paver. This suggests that each variable is significant and should be controlled by construction specifications. Particularly significant was the observation that these variables can be controlled so as to prevent accumulation of foam and excess mortar while at the same time achieving a surface requiring only occasional and minimal hand finishing. It is likely, however, that the interrelationships between the multitude of vibrator and concrete variables involved are so complex that precise specification controls may be impractical. If future research shows this to be the case, control will continue to depend solely on the judgment and experience of the individuals involved in the paving operation.

As mentioned previously, vibrator spacing was not included as a variable in this study. However, the differences in concrete property measurements for samples from in and between vibrator paths indicate that closer spacing than was used in this test is desirable. Especially significant was the lower strength of the upper half of cores from between vibrators. Until the effect of spacing is better defined, the current specification of a 2-foot maximum should be followed. This requires at least six vibrators per 12-foot pavement lane.

IMPLEMENTATION

This study provided insight into the significance of various factors involved in the use of internal vibration to consolidate pavement concrete. While this insight gave some indication of an optimal combination of vibrator frequency and eccentric size, all combinations used in the study appeared to produce adequate consolidation. As a result, no specifically implementable item was forthcoming from the study.

However, the study observation that paver speed and vibrator frequency can be controlled so as to prevent accumulation of foam and excess mortar, while still achieving a good surface behind the paver, was significant and should be brought to the attention of those directly involved in concrete paving. In this respect, the observation has been discussed with engineers in the Bureau of Construction and will be brought to the direct attention of the Districts and Regions through this report and the memorandum transmitting it to them.

FUTURE RESEARCH

The consolidation of concrete by internal vibration has been shown to be an extremely complex phenomenon that will require extensive, fundamental research before it is completely understood. However, the results of this study indicate that within normal ranges of vibrator frequency, paver speed, and eccentric size, adequate consolidation without excess air loss and segregation can be expected. Nevertheless, two factors, not directly included in the study, would appear to provide an area of needed and potentially fruitful research. These are vibrator spacing and depth of concrete surcharge above the vibrators.

The properties of concrete in a pavement are normally considered to vary randomly throughout the slab. In this study, however, a pattern of variation was observed in that the properties of cores taken from in the vibrator path were statistically different than the properties of cores from between vibrators. The lower strengths of the concrete in the upper portion of the pavement between vibrators is of particular concern. This suggests a vibrator spacing somewhat less than that used in the test should be specified. In this regard, a study to determine maximum acceptable vibrator spacing is recommended. Hopefully, however, some indication of this maximum will be forthcoming when the FHWA analyzes the data from all the states participating in the program for which this study was a part.

The depth of concrete over the vibrators is known to be a critical factor in achieving complete consolidation with internal vibration. Unlike surface pan vibrators, the internal vibrator does not have sufficient mass of its own to drive the vibrational energy to any appreciable depth in the concrete. This mass must be provided by the concrete above the vibrator. Some minimum head of concrete is, therefore, necessary to achieve consolidation throughout the pavement.

In the current study, concrete surcharge depth was not a controlled variable but was measured at each test location. These depths above the vibrators, which varied from 5 to 11 1/2 inches with an average of 8.6 inches, were included in the correlation analyses of the measured concrete core properties. In no instance was concrete head found to be statistically significant. This might be taken to indicate that any depth within the range included in the test is adequate. Nevertheless, it is suspected that the surcharge above the vibrators should be at least as great as the concrete depth below the vibrators. Further research is needed to determine this minimum depth.

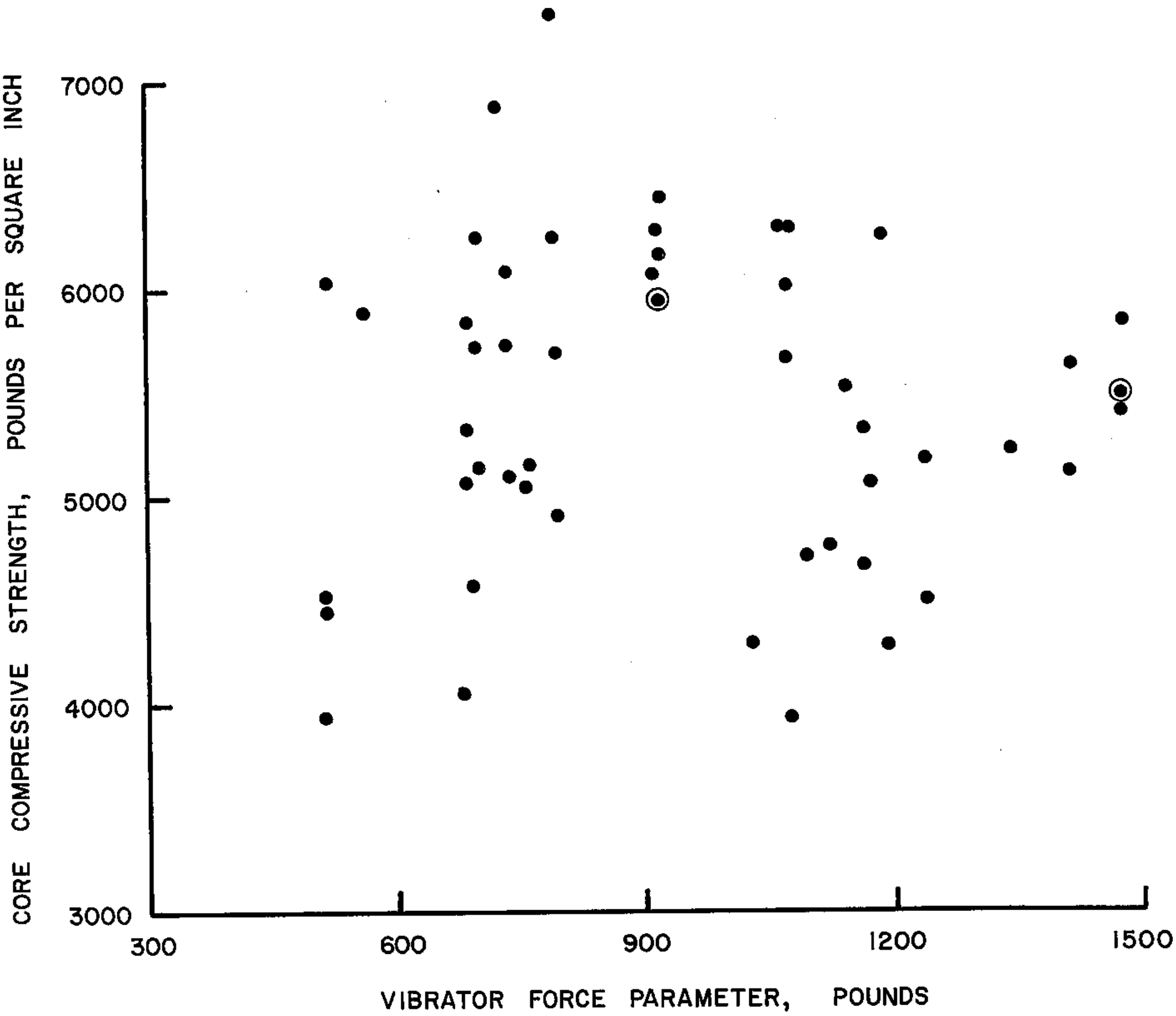

FIGURE 3. COMPRESSIVE STRENGTH OF THE BOTTOM HALF OF CORES FROM BETWEEN VIBRATORS VERSUS VIBRATOR FORCE PARAMETER

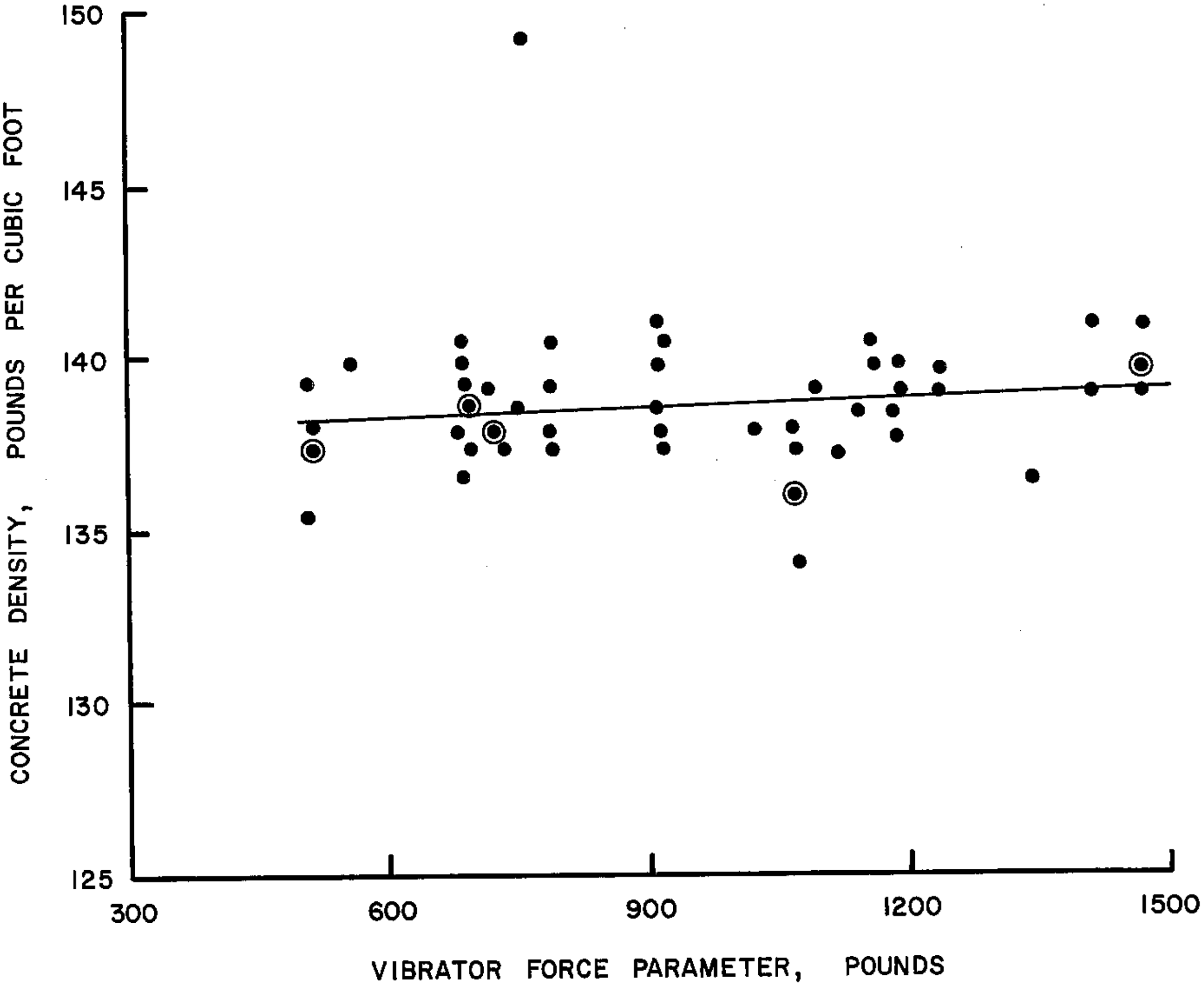

FIGURE 4. DENSITY OF THE UPPER HALF OF CORES FROM THE VIBRATOR PATH VERSUS VIBRATOR FORCE PARAMETER

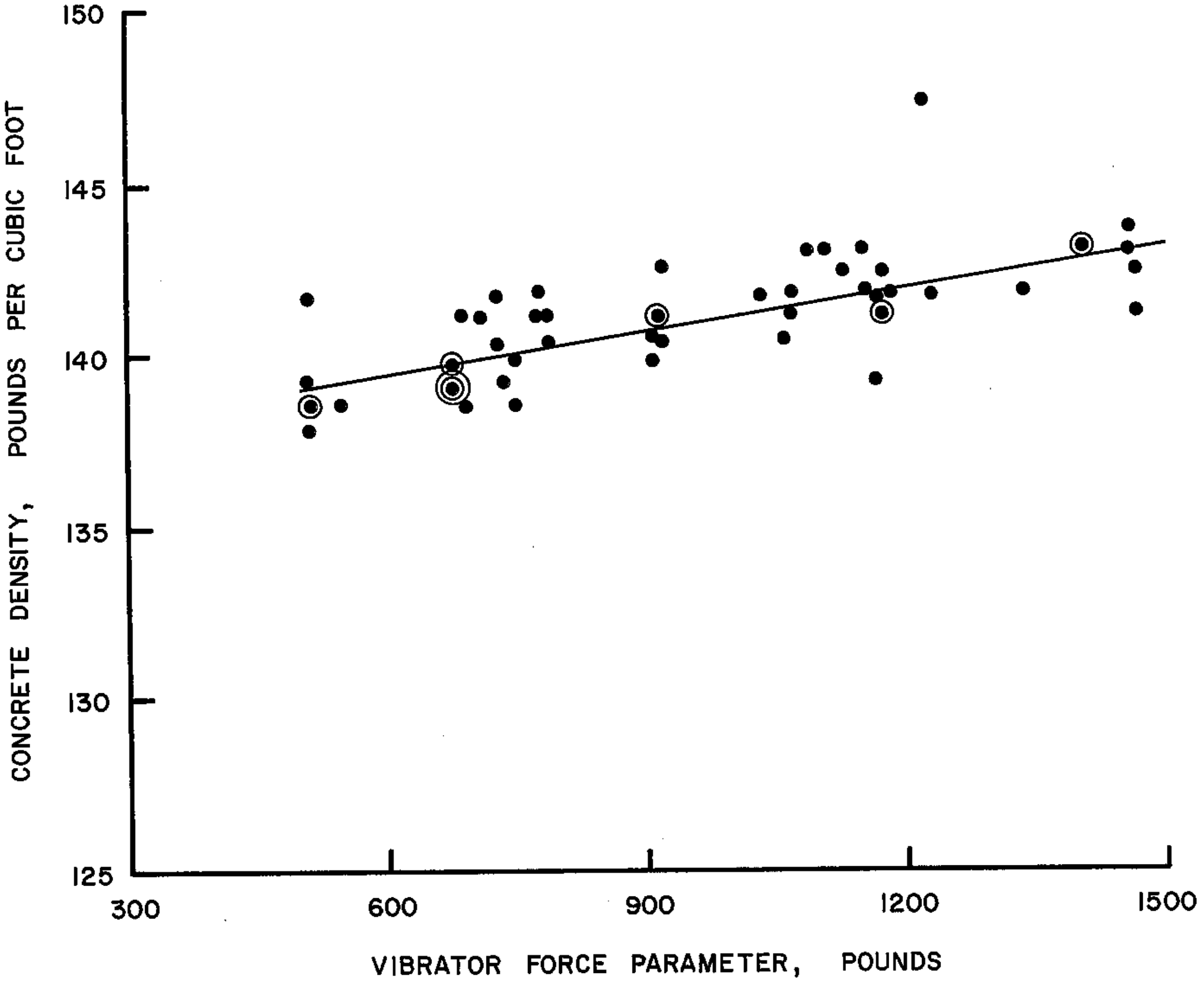

FIGURE 5. DENSITY OF THE BOTTOM HALF OF CORES FROM THE VIBRATOR PATH VERSUS VIBRATOR FORCE PARAMETER

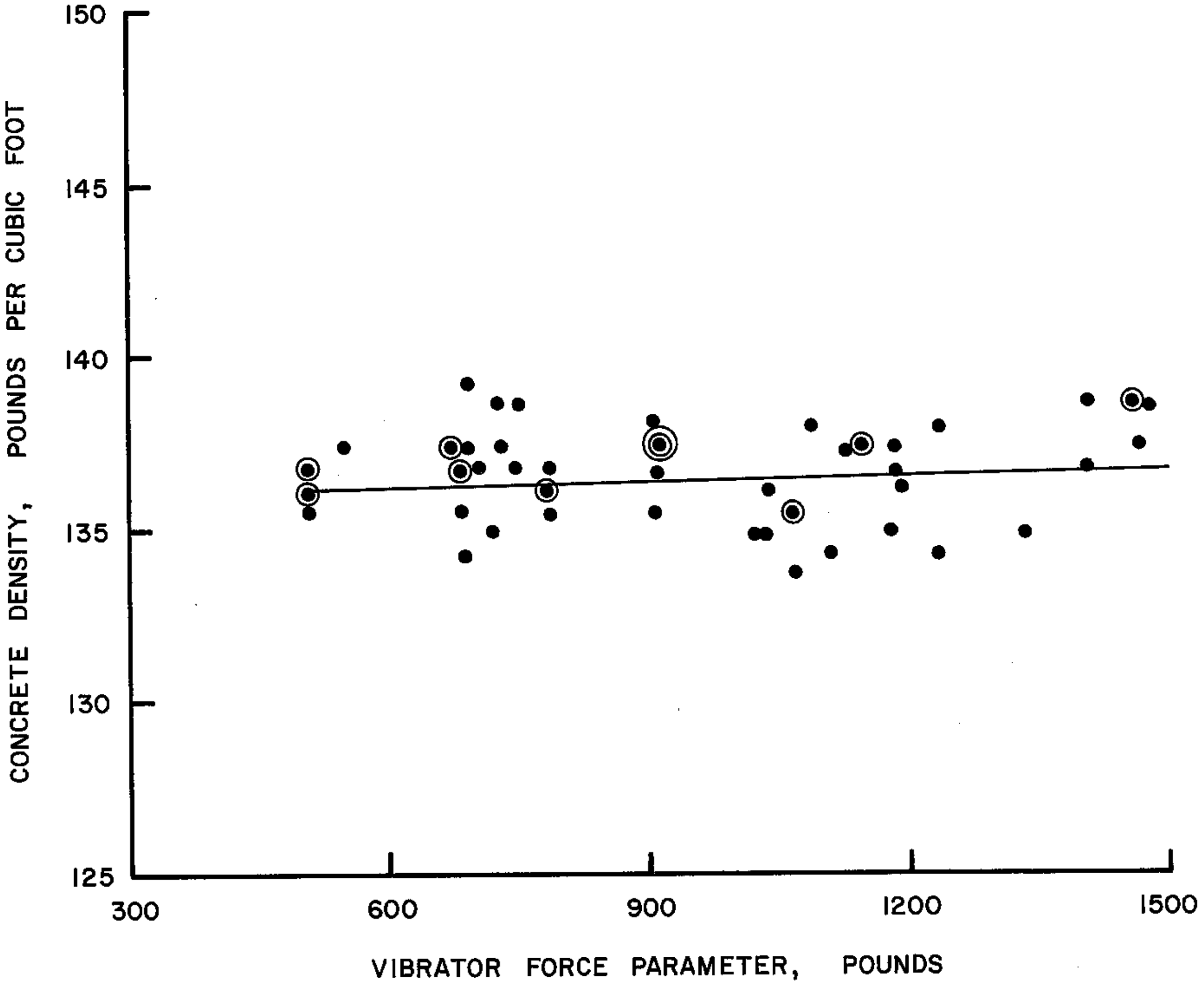

FIGURE 6. DENSITY OF THE UPPER HALF OF CORES FROM BETWEEN VIBRATORS VERSUS VIBRATOR FORCE PARAMETER

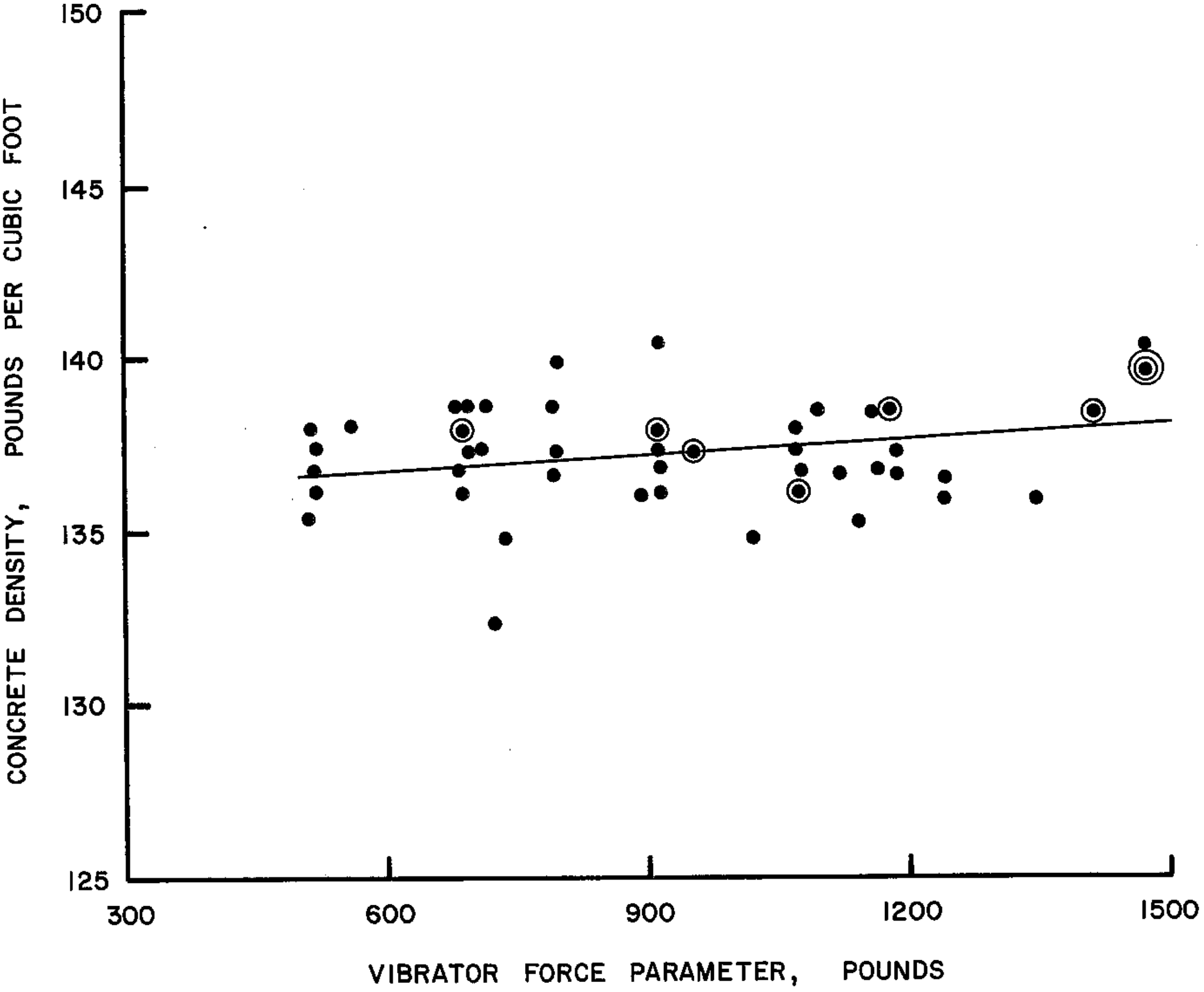

FIGURE 7. DENSITY OF THE BOTTOM HALF OF CORES FROM BETWEEN VIBRATORS VERSUS VIBRATOR FORCE PARAMETER

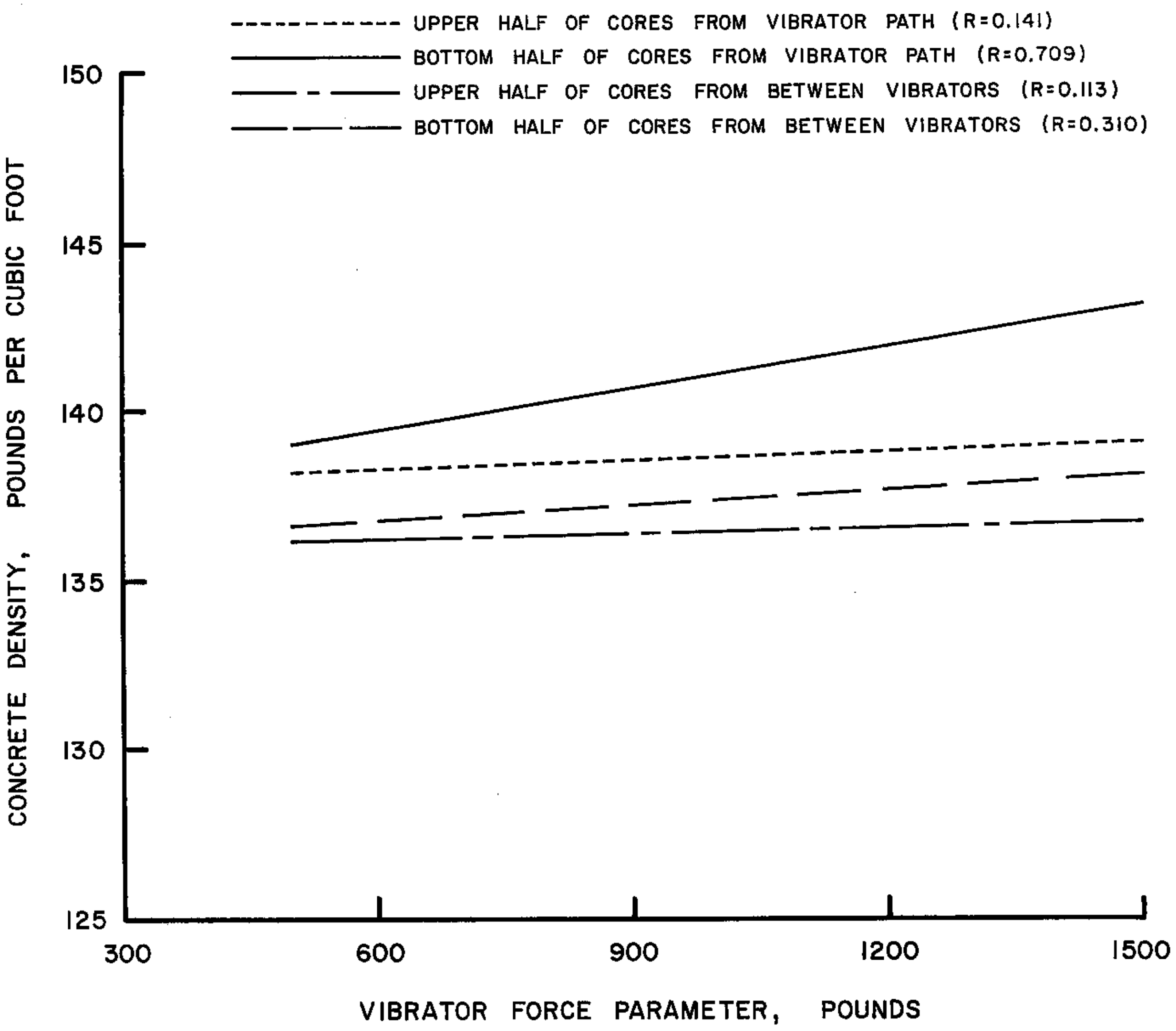

FIGURE 8. COMPARISON OF THE CORE DENSITY VERSUS VIBRATOR FORCE PARAMETER REGRESSION LINES

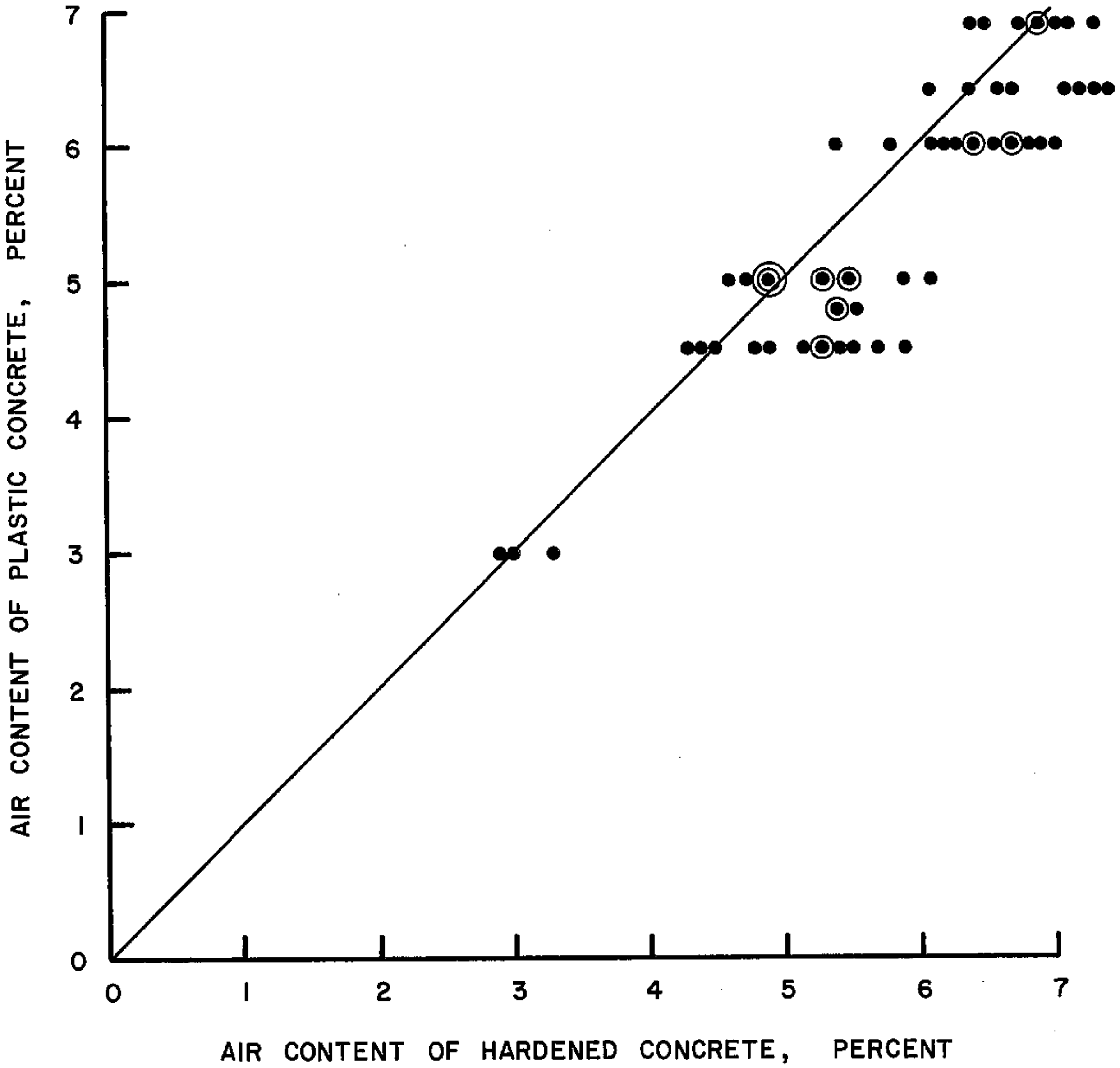

FIGURE 9. CALIBRATION DATA FOR HIGH PRESSURE AIR METER

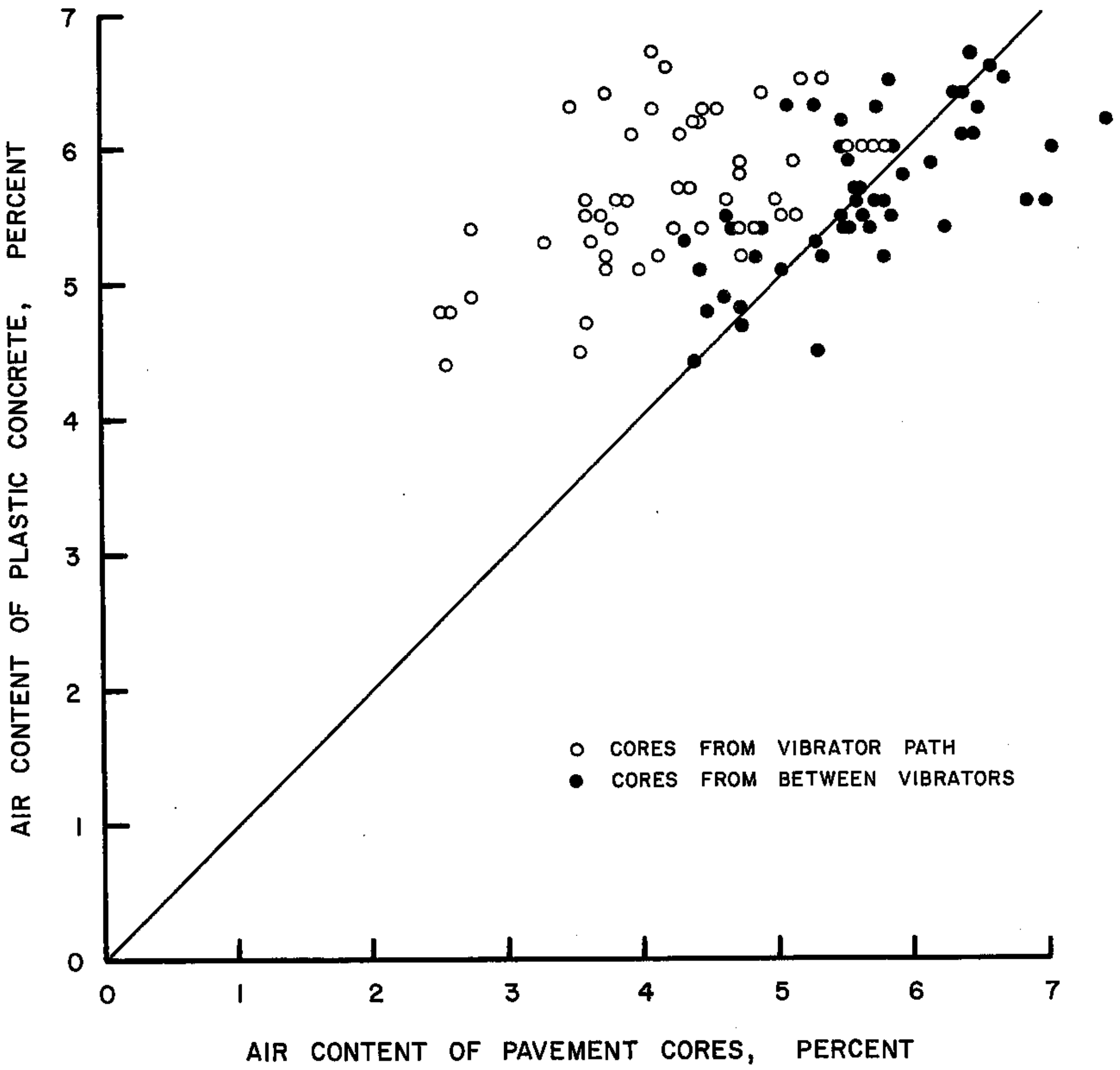

FIGURE 10. AIR CONTENT OF PLASTIC CONCRETE VERSUS AIR CONTENT OF CORES

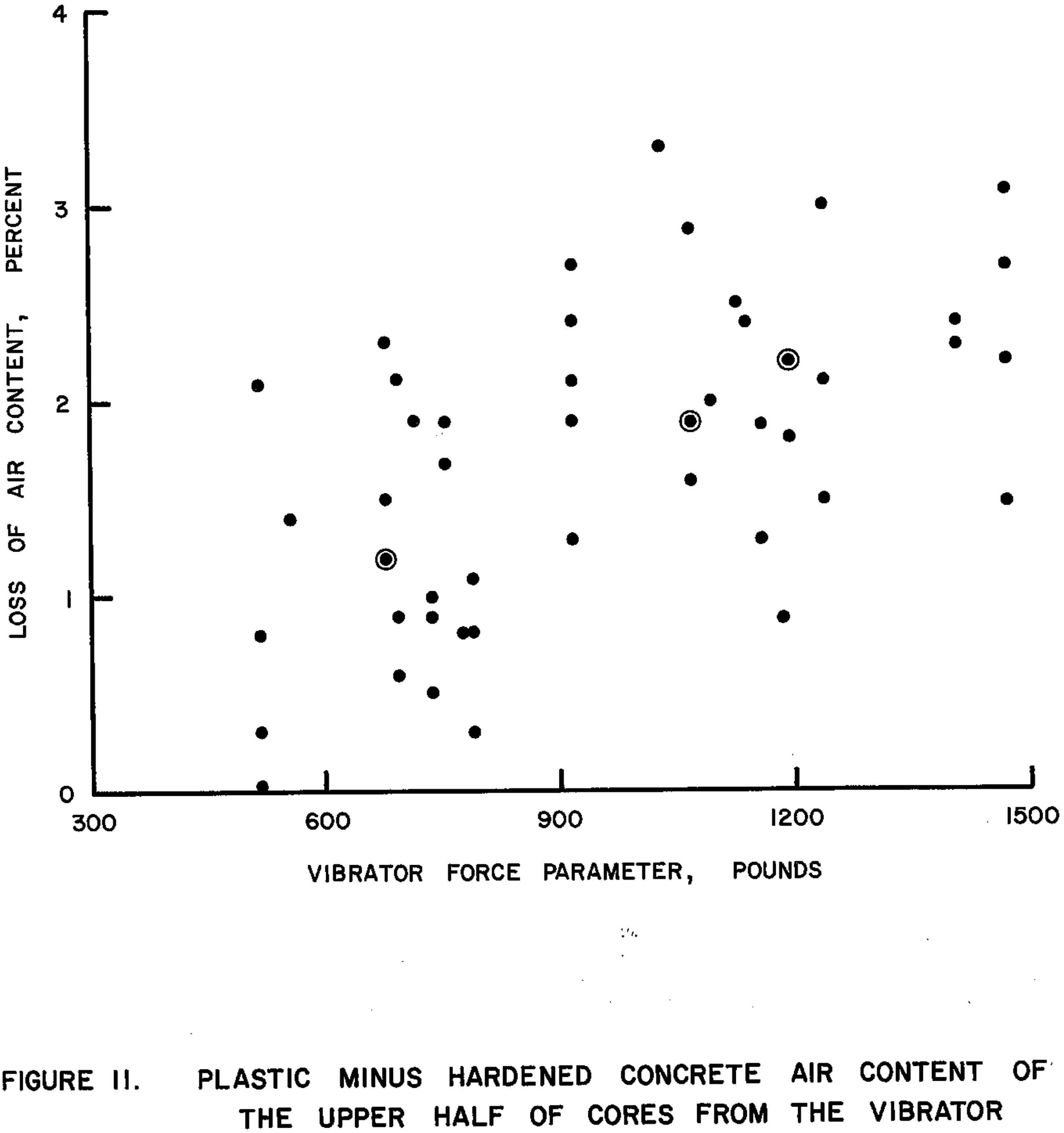

FIGURE 11. PLASTIC MINUS HARDENED CONCRETE AIR CONTENT OF THE UPPER HALF OF CORES FROM THE VIBRATOR PATH VERSUS VIBRATOR FORCE PARAMETER

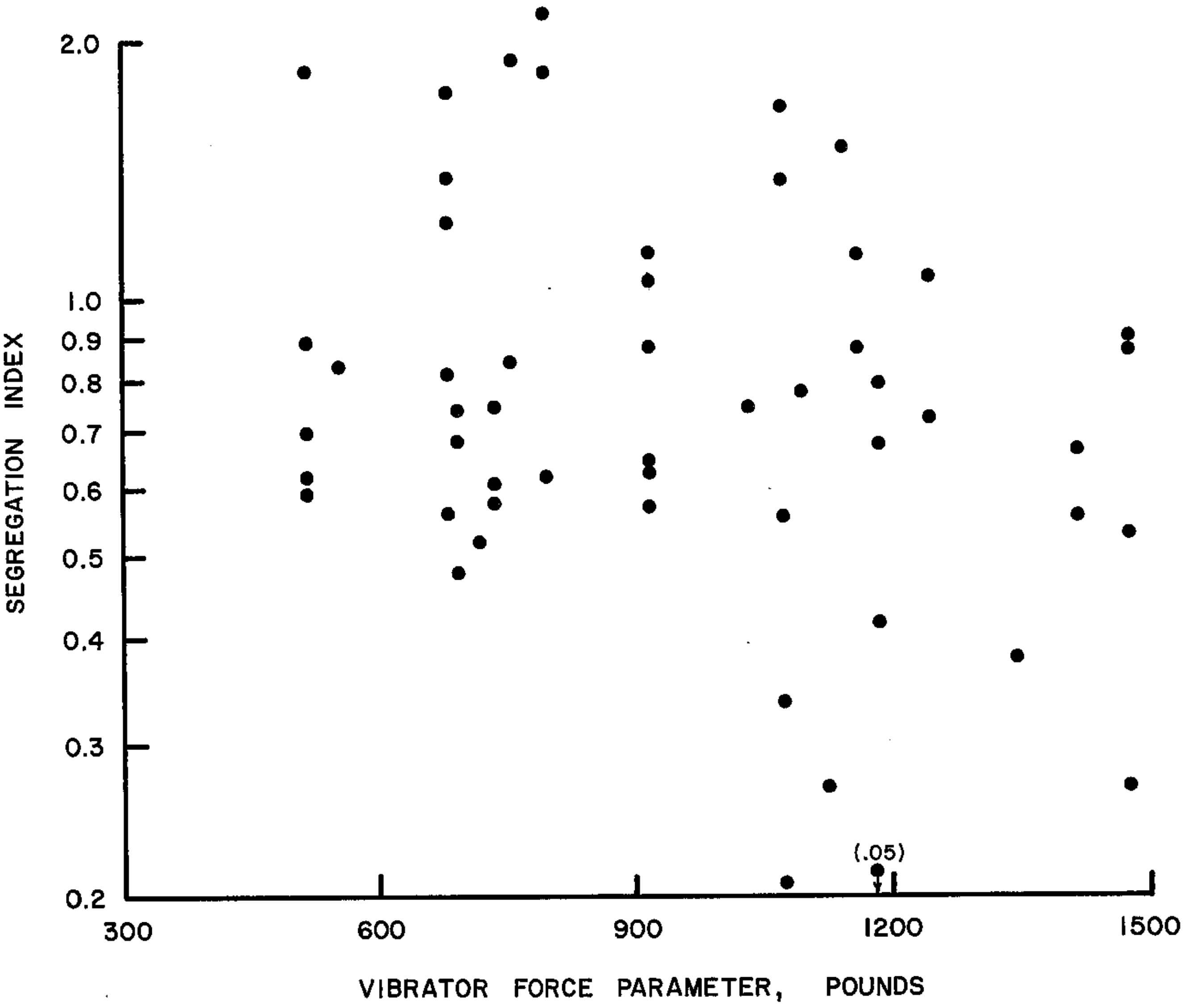

FIGURE 12. SEGREGATION INDEX OF CORES FROM THE VIBRATOR PATH VERSUS VIBRATOR FORCE PARAMETER