VOID PARAMETERS OF 24 CORES OF CONCRETE REMOVED FROM A CONSOLIDATION TEST STUDY SECTION OF I-64

by

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SUMMARY

During the construction of I-64 near Charlottesville, Virginia, the Ballenger Paving Company chose to set up a limited experiment to investigate various factors affecting the consolidation of concrete by vibration. The test design varied the speed of the paver and used vibrations at several frequencies. Speeds of 3, 4.25, 5.5, 11, 12, and 14 feet per minute and frequencies ranging from 7,800 to 10,100 revolutions per minute were used in 6 test sections. When the experiment was initiated it was anticipated that differences in the concrete which were related to the variations in vibration would be reflected in the results of conventional measurements of density and void content made on cores removed from each of the test sections. The unit weights determined on the cores indicated large variations in void content across the width of the pavement at a given station. In the hope of determining whether the variations in unit weight were due to variations in the air void system or to segregation of the aggregate, the Research Council was asked to make micrometric air void and aggregate analyses on 24 core samples.

The analyses showed that for any particular concrete the faster the motion of the vibrators through the concrete and the greater the spacing the less will be the consolidation. Between batches, it was found that the greater the slump or workability, the greater the consolidation achieved by a set of vibrator conditions. The frequencies of the vibrators used covered such a narrow range that no correlation between frequency and consolidation was possible.

Insufficient sampling precluded the determination of aggregate segregation. Although the numerical results of the void determinations and correlations with vibration parameters are not statistically defensible, the trends obtained appear reasonable and valid and should be helpful in establishing general relationships. The results are presented in numerical form to provide data as to the order of magnitude of the interactions of the factors involved in the consolidation process.

For the type of concrete and kind of vibrators used, the data seem to indicate that if the slump approaches 1-inch then the forward speed of the vibrator screed should be no more than 6 feet per minute when the spacing of the vibrators is about 2 feet. Higher speeds will probably produce high void, less abrasion resistant areas of pavement.

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INTRODUCTION

The need for consolidation to remove excess voids from pavement concrete is well-known. Voids are usually designated as "entrapped" or "entrained". Although the distinction is not exact, voids which are irregular and greater than 1mm in diameter are usually considered as entrapped; and smaller, spherical voids are classified as entrained. The entrapped voids are largely eliminated from concrete by sufficient consolidation. If proper levels of entrained air and water-cement ratios are used, greater density of concrete will provide higher strength and greater resistance to abrasion. Studies made by Bower and Gerhardt of 4 heavily traveled pavements in Colorado showed that the amounts of consolidation effort expended in finishing the pavement were directly related to the ability of these pavements to resist abrasion.(1) However, purposely entrained air can be partially removed by excessive vibration and when this occurs the ability of pavement to resist freeze-thaw and salt damage may be adversely affected.

Proper consolidation is, therefore, that densification effort which will produce concrete with a very low percentage of large voids (no honeycombs, 'rat holes' or bleed channels), the intended amount of entrained air, even distribution of the aggregate, and proportioned unit weight.

In July 1971 ACI Committee 114, Research and Development,(2) stated that high on the list of the research subjects of most critical importance is the study of the consolidation of fresh concrete. The following is quoted from that committee's call for such research.

> The properties of hardened concrete and its performance in a structure are critically affected by the methods of consolidation used during placement. Elimination of internal and surface voids, achievement of complete bond with reinforcing steel and previously placed concrete, and optimum strength and impermeability are primary objectives.

> At the same time, compactive effort must not be uneconomically excessive or improper for the particular placement conditions lest harmful bleeding and segregation occur. The ideal economical solution would be to apply exactly the correct amount of the right kind of compaction, but no more, to assure maximum enhancement of the benefits.
>
> ACI Committee 309, Consolidation of Concrete, has called attention to the lack of quantitative information to permit reliable decisions as to methods and amount of compaction needed for a particular structural element. Among the factors needing detailed study are: methods of measuring degree of consolidation and determining the volume of concrete affected by vibration in any given procedure; amount of energy required for vibration to fluidize the concrete mass; factors affecting the transmission of vibratory energy through fresh concrete, and its rate of attenuation; the resonant frequency of the vibrating system and the variables which affect it; influence of such characteristics as aggregate size, mixture proportions, and consistency of the concrete on the response to vibration; and the relative efficiency and economy of various vibration methods.

The American Concrete Institute Recommended Practice for Consolidation of Concrete, dated December 1971, gives a wide range of parameters within which high quality consolidation is most apt to be produced. This recommended practice states that the degree of densification should be controlled by frequent inspection and by testing for proper entrained air content and, if necessary, changes should be made in the vibrating procedures or in the mix design.

The factors which influence the degree of consolidation obtained by vibration include the following:

1. Type of vibrator
    a. size of head
    b. frequency
    c. amplitude
    d. force

2. Spacing between vibrators

3. Speed with which the vibrators are moved through the concrete

4. Workability of the mixture (slump)

5. Aggregate
   a. size
   b. density
   c. grading

6. Amount of entrained air

The effect of each of these factors and their interaction on each other have not been completely ascertained although considerable insight has been gained by theoretical and experimental studies.(1,3,4,5,6) Because of the complexities of these interactions, specifications for pavements are generally vague and contain statements such as "good consolidation", "proper vibration", etc.

The specifications of the Virginia Department of Highways concerning consolidation state:(3)

> Sec. 321.03 (g) <u>Vibrators</u> Vibrators for full width vibration of concrete pavements, shall be internal type with multiple spuds. They may be attached to the spreader, or may be mounted on a separate carriage operating directly behind the spreader. The frequency of the vibrators shall not be less than 7,000 impulses per minute unless otherwise approved by the engineer . . . .

And further —

> Section 321.07 <u>Placing Concrete</u> . . . Concrete shall be thoroughly consolidated against and along the faces of all forms and along the full length and on both sides of all joint assemblies by means of full width vibration in accordance with the requirements of Section 321.03 (g) . . . .

In general, it is expected that the relationship between the amount of consolidation, air void content, and physical properties conforms to the pattern shown in Figure 1.* Air voids do not start to leave the concrete until a considerable amount of vibratory effort has been expended. The coarser voids can be almost completely removed. A certain portion of the finer voids cannot. As the vibration becomes more effective, the concrete is apt to become segregated. Mortar and, most especially, paste will probably tend to move towards the vibrators and coarse aggregate

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* All figures and table attached.

will probably tend to move away from the vibrators and to sink. The effect of the removal of the voids is complex because resistance to freezing and thawing increases with increased entrained air while strength and resistance to abrasion decrease. It is generally conceded that the coarser voids removed during normal vibration are not those beneficial to durability.

BALLENGER PAVING COMPANY EXPERIMENT

During the construction of I-64 near Charlottesville, Virginia, the Ballenger Paving Company chose to set up a limited experiment by varying the speed of the paver and using vibrators at several different frequencies. Speeds of 3, 4.25, 5.5, 11, 12, and 14 feet per minute (fpm), and frequencies ranging from 7,800 to 10,100 revolutions per minute were used in 6 test sections.(8) The pavement was 8-in. thick continuously reinforced concrete (0.6% longitudinal steel, no transverse steel). Slip form operations were used to place the pavement in a 24-ft. width.

When the experiment was initiated, it was anticipated that differences in the concrete which were related to variations in vibration would be reflected in the results of conventional density and void content determinations on cores removed from each of the test sections. A portion of the report of this experiment, prepared by Robert Bruce, is attached as the Appendix. This portion contains details of the results of their analyses of the 24 core samples. These analyses included density measurements and determinations of the modulus of elasticity by sonic methods. Four core samples were obtained from each test section.

The location of these samples relative to that of the vibrators and the several paver speeds has been plotted in Figure 1. It can be seen that almost every core represented a unique combination of paver speed, distance from vibrator, slump, air content, etc., so that there is actually no replication of conditions among the samples.

As evidenced in the second table quoted in the Appendix from Bruce's report, the unit weights determined on the cores indicated a large variation in void content across the pavement at a given station. In the hope of determining whether the variation in unit weight was due to variations in the air void system or to segregation of the aggregate, the Research Council was asked to make micrometric air void and aggregate determinations on the 24 cores. It was hoped that the analysis of these cores would provide an indication of what kind and degree of consolidation effort should be specified in order to produce a durable concrete pavement.

RESEARCH COUNCIL ANALYSES

Procedures

The cores used in the tests described in Bruce's report were delivered to the Research Council laboratory. Each core was cut horizontally in 4 places to produce a 1-inch thick top slab and three $1\frac{1}{4}$- to 2-inch thick lower slabs. An effort was made to avoid cutting reinforcing steel. The underside of each slab (Figure 3) was finished to a finely ground surface and a linear traverse analysis of the void system was made using the procedures outlined in ASTM C457. Fifty inches of traverse were examined on each slab. It was determined that the greatest variability in the void system was in the top 2 slabs and most particularly in the second slab, that is, at about a $3\frac{1}{2}$-inch depth and above. The top 2 slabs were etched in 0.3 N HCl for 20 seconds and the surfaces were subjected to a linear traverse analysis of the aggregate distribution. About 15 inches of traverse were examined on each slab. Half of this traverse length was at right angles to the other half.

Results

As expected, the void contents of the cores were found to be directly related to the distances the cores were from the nearest vibrators, directly related to the forward speed of the screed, and inversely related to the slump. No relationship could be found between the frequency of the vibrators and the void contents. The void content was plotted against a variety of expressions containing these variables. The best relationship was obtained by a factor of the form

$$CF = \frac{d_1 \times d_2 \times Sr}{sl}$$

where CF = consolidation factor

d_1 & d_2 = distances to nearest vibrators

Sr = relative speed or $\dfrac{\text{test forward speed}}{\text{lowest forward speed}} = \dfrac{\text{test speed}}{3}$

sl = slump, in inches

The best curves were obtained when the log of CF was plotted against the percent voids.

No theoretical basis for this factor is proposed nor have precedents been found in research reports. Throughout the remainder of this report it will be designated as the consolidation factor. The consolidation factor was empirically derived from the void data and cannot be expected to be valid for conditions differing widely from those found in this experiment. Other sets of experimental conditions would probably clarify the effect of vibrator frequency on void content and aggregate segregation.

Figure 4a shows the relationship between the consolidation factor and the total void contents of the cores and Figure 4b shows the data available for voids over 1mm in diameter. Core sample #17 was removed from the pavement at a location which could be expected to have undergone vibration of an intensity indicated by a factor of 0.13. The 7% air voids present may indicate a malfunction of the nearest vibrator.

The data from each level were plotted separately against the consolidation factor (see Figure 5). It may be seen that there is a variation in void content vertically as well as laterally. The best correlation was found in the second level down and none can be discerned in the fourth level. The data were extrapolated to provide curves for each of the top 3 levels and 3 curves sketched together in Figure 6. The second level is shown to be the area most consolidated (containing least voids) for a given set of vibration parameters. The combined data for each core sample are shown in Figure 7, and it can be seen that in general in the cores most exposed to the vibrators (those in the lower portion of graph) the lowest void content is in the second slab (about $3\frac{1}{2}$ inches from the surface).

The aggregate content data were analyzed by the same methods but no correlation between void content or consolidation factor could be found. Because the effect of vibration on void content was most noticeable at the $3\frac{1}{2}$-inch depth, the aggregate content at this level was studied separately. No correlation between aggregate content and any vibration parameter was found. It must be recognized that only 15 inches of linear distance were examined on a 4-inch diameter surface and it may be that the scatter of these data and lack of correlations merely indicate insufficient sampling.

DISCUSSION

The best correlation between the unit weight and void data in Bruce's report and the void content data obtained by linear traverse at the Research Council was arrived at by comparing the specified unit weight with the unit weights as measured by the simple weighing and measuring procedure, calculating the indicated percent voids, and plotting them against the voids as measured by the linear traverse. These data are presented in Figure 8. Void contents of over 7% showed excellent correlation. Many of the cores with less than 7% voids had weights which were high with respect to their void content. This may have been due to aggregate concentrations. The three worst discrepancies were with cores 1, 2 and 7, which are among the cores with the higher coarse aggregate contents. However, cores 22 and 17 have equally high coarse aggregate contents but show little discrepancy between the measured void content and the calculated void content. Perhaps the aggregate content data are faulty because of insufficient sampling. This is discussed later. The steel in the cores showed no consistent effect.

Figure 9 shows the poor correlation found between the core density (wt/ft^3) and consolidation factor. The dotted line indicates the expected correlation only. These data are obviously too scattered to indicate the true position of this curve.

Figure 10 is a bar graph which by regrouping the data illustrates part of the meaning of the consolidation factor. The samples affected by higher speeds of the screed — 11, 12 and 14 fpm — are plotted in the right-hand portion of this figure and those affected by the lower speeds — 3, 4.25 and 5.5 fpm — in the left-hand portion. Void contents of the top 3 slabs of each core as determined by the linear traverse method are shown vertically and the distance of the sample from the nearest vibrator path horizontally. If core #17 is ignored, it can be seen that both the distance from the vibrator path and the speed of the paving screed have an effect on the amount of consolidation.

A more intensive testing program designed according to statistical theory and including core samples of replicate conditions would provide statistically defensible answers of more quantitative precision than has this present study. However, such a program would be quite costly. It is estimated that if it were decided that the precision now obtained in the determination of the segregation of total voids was to be required for coarse aggregate and for voids over 1mm in diameter, then 12 times as much surface area of concrete would have to be examined for each sample as was examined for this report. If twice as much prepared surface was produced and analyzed on each core, six 4-inch cores would be required per sample. If the variables in this intensive testing program were limited, by keeping the slump and vibration constant and including only 2 paver speeds, 3 spacings of vibrators, 3 distances of samples from the vibrator, and only one replication, 216 cores would be required. While this would permit quantitative conclusions for the project under consideration there would be doubt that generalizations to other conditions would be valid.

The trends obtained from this study appear reasonable and valid and whether further refinement is warranted is a matter for debate.

Thus the results from this study are helpful in establishing the general relationships and trends in numerical form which provide data as to the order of magnitude of the interactions of the factors involved in the consolidation process.

If for the sake of discussion we hypothesize that curves drawn from sufficient data would approximate the curves shown in this report, and if we assume that the consolidation factor used herein has the appropriate formula for the experimental conditions used, then by examination of Figure 4b we might wish to conclude that nearly all of the large diameter voids are driven out at a factor of 0.2, that sufficient large voids are removed at 2.0, and therefore a desirable consolidation factor would be one between 0.2 and 2.0. Further, we might desire to construct a table similar to Table 1 and a graph as in Figure 11.

It is realized that the consolidation factor discussed herein does not take into account the finite limit of the range of effectiveness of vibrators. The radius of this limit is unknown but assumed to vary with the consistency of the concrete and the parameters of the vibrators including frequency. It can be shown mathematically that for the vibrators and concrete of this experiment the consolidation factor would no longer be valid for spacings of vibrators of over 36 inches.

CONCLUSIONS

The data obtained at the Research Council confirm the expected result that for any particular concrete, the faster the motion of the vibrators through the concrete and the greater the spacing, the less will be the consolidation. Between batches, it may be seen that the greater the slump or workability, the greater will be the consolidation achieved by a set of vibrator conditions. The frequency of the vibrators used in this test covered such a narrow range that no correlation between frequency and consolidation was possible.

Insufficient samples precluded the determination of aggregate segregation.

For the type of concrete and kind of vibrators used, the presently available data (see Figure 7, 10 and 11) seem to indicate that if the slump approaches 1 inch then the forward speed of the vibrator screed should be no more than 6 fpm when the spacing of the vibrators is about 2 feet or high void, less abrasion resistant areas will result. For faster speeds, the spacing between vibrators should be decreased. Vibratory methods much in excess of this may possibly lower the air content of the concrete below that needed to prevent freeze-thaw damage.

ACKNOWLEDGEMENTS

B. F. Marshall, highway materials technician, skillfully prepared the 4 finely ground surfaces which were examined on each sample and made the lengthy and detailed micrometric analyses by the use of the linear traverse method. His many hours of skilled and patient work are much appreciated.

This study was conducted under the supervision of the head of the Council's Concrete and Petrography Section, Howard H. Newlon, Jr., assistant state highway research engineer. His encouragement and suggestions were most necessary for the successful completion of this data analysis and report.

The study was financed by Virginia Department of Highway funds.

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2. ACI Committee 114, Research and Development, "Recommended Research and Development Program on Consolidation of Fresh Concrete," American Concrete Institute Journal, July 1971.

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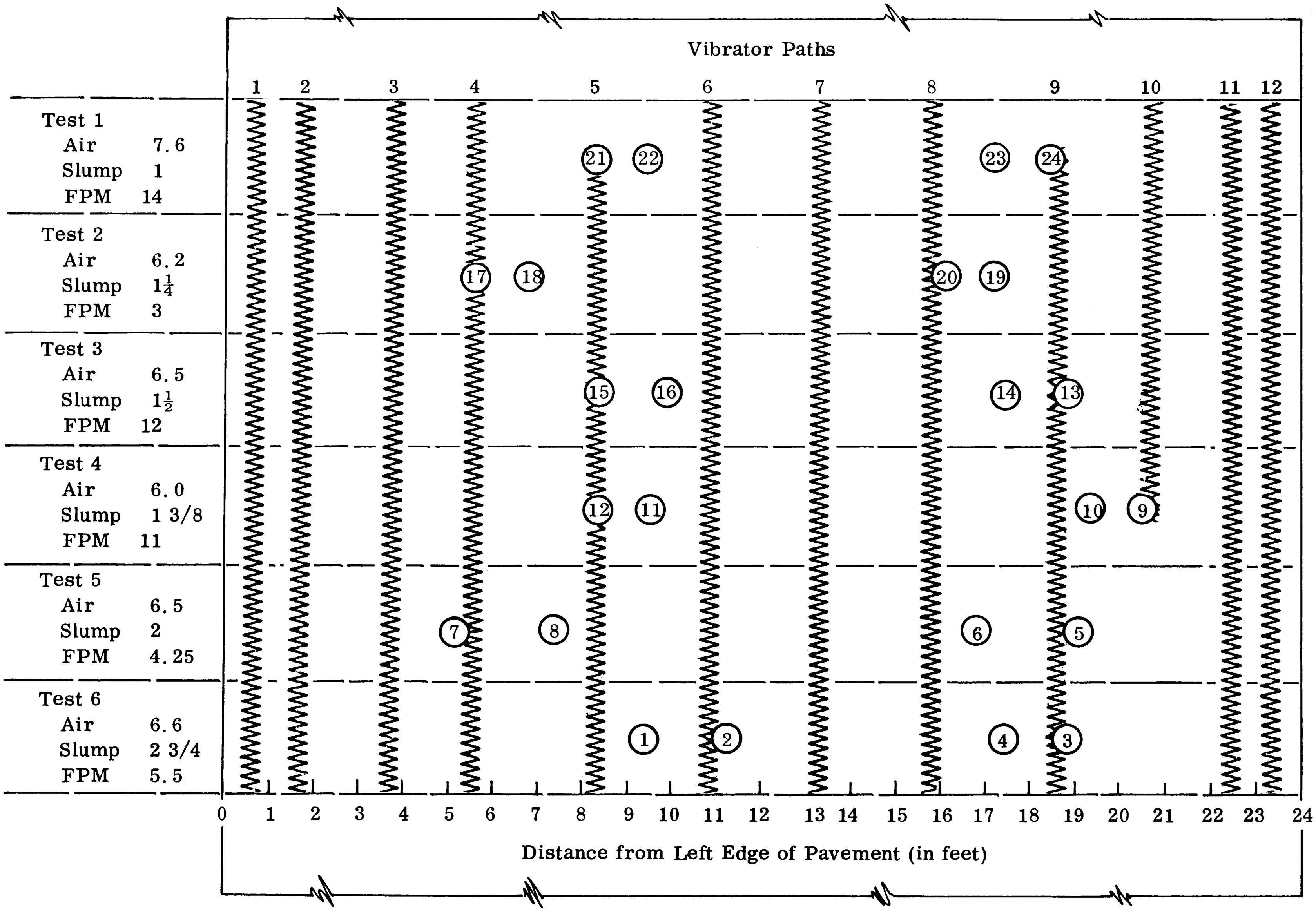


Figure 1. Location of core samples.

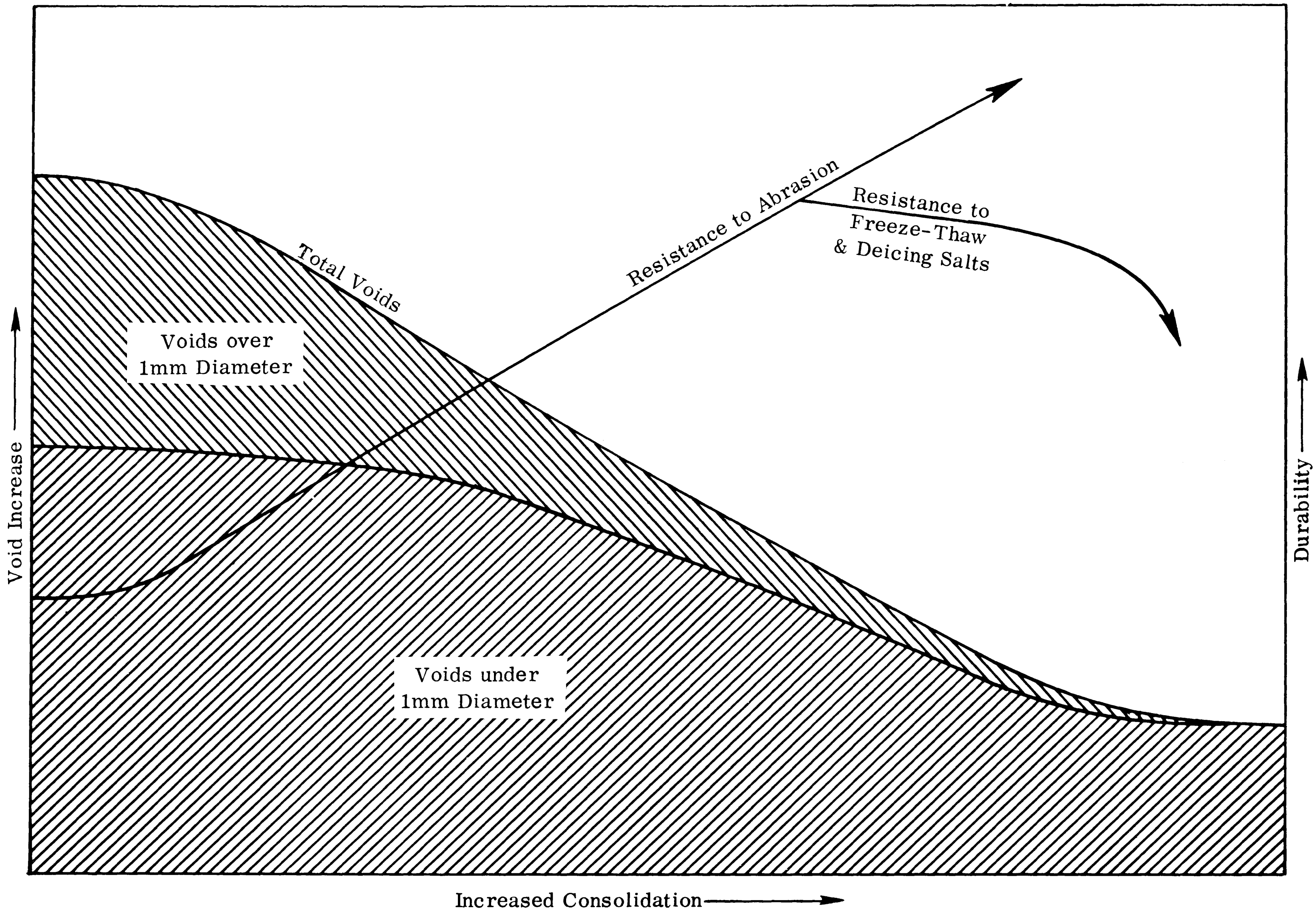


Figure 2. Expected relationship of durability to amount of consolidation.

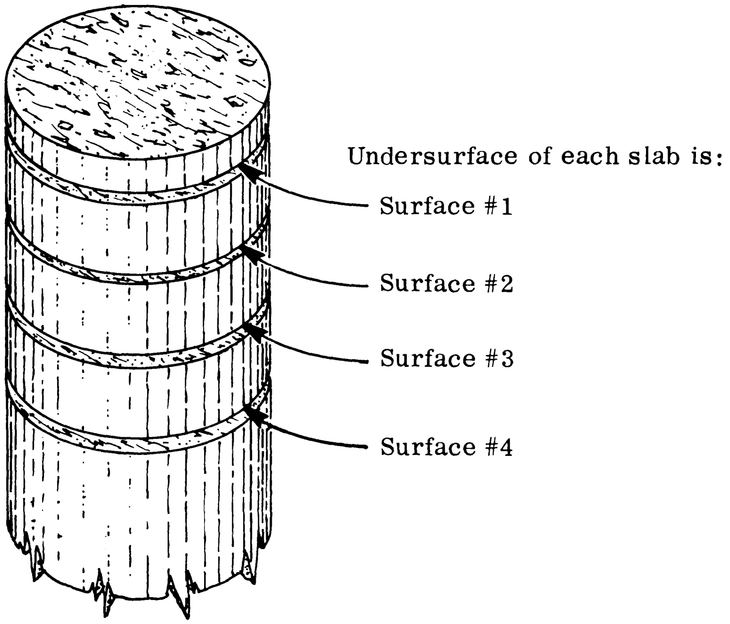


Figure 3. Sketch of the position of examined surfaces of the core samples.

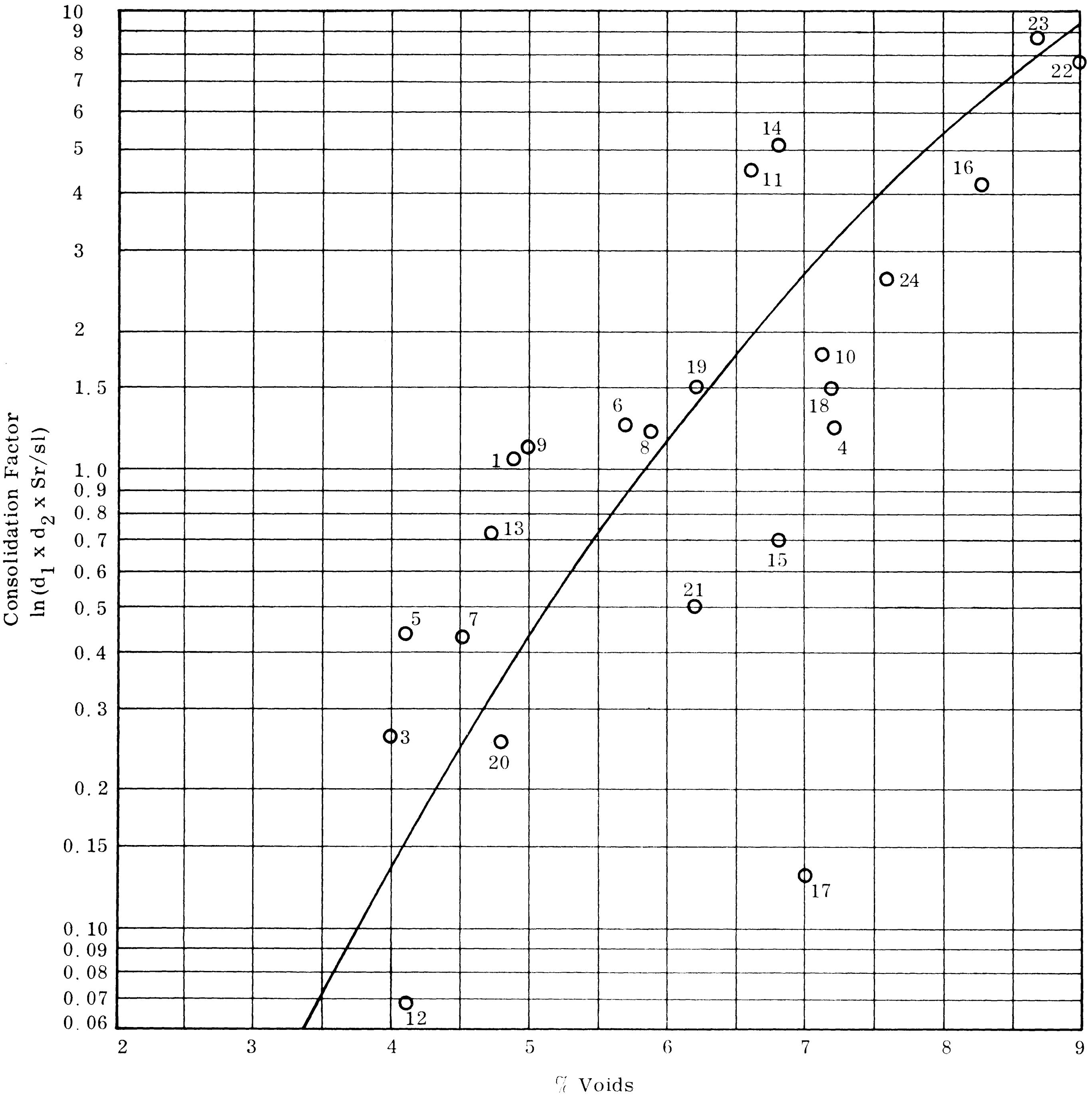


Figure 4a. Relationship between the consolidation factor and the total void content of the 24 core samples as measured by the linear traverse.

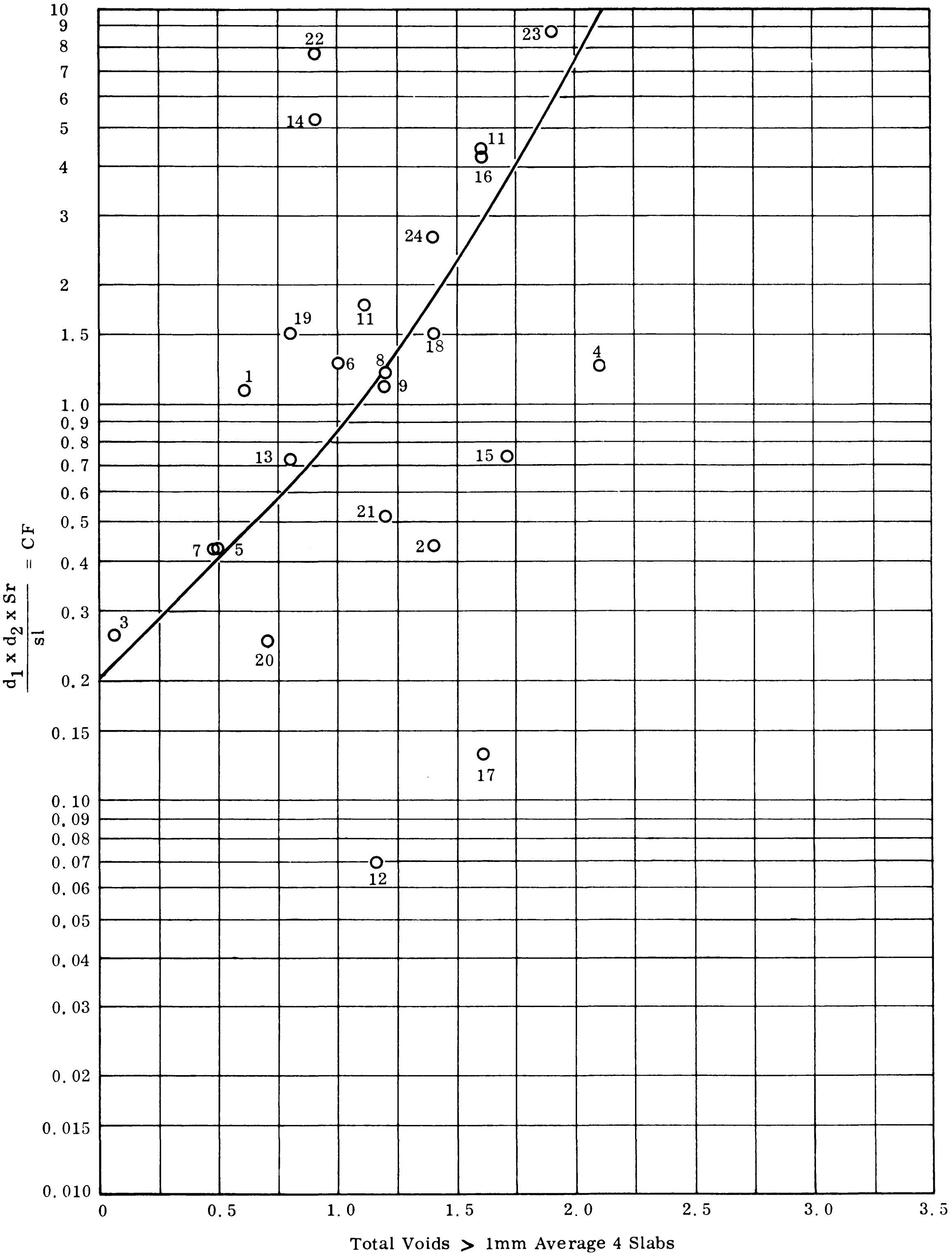
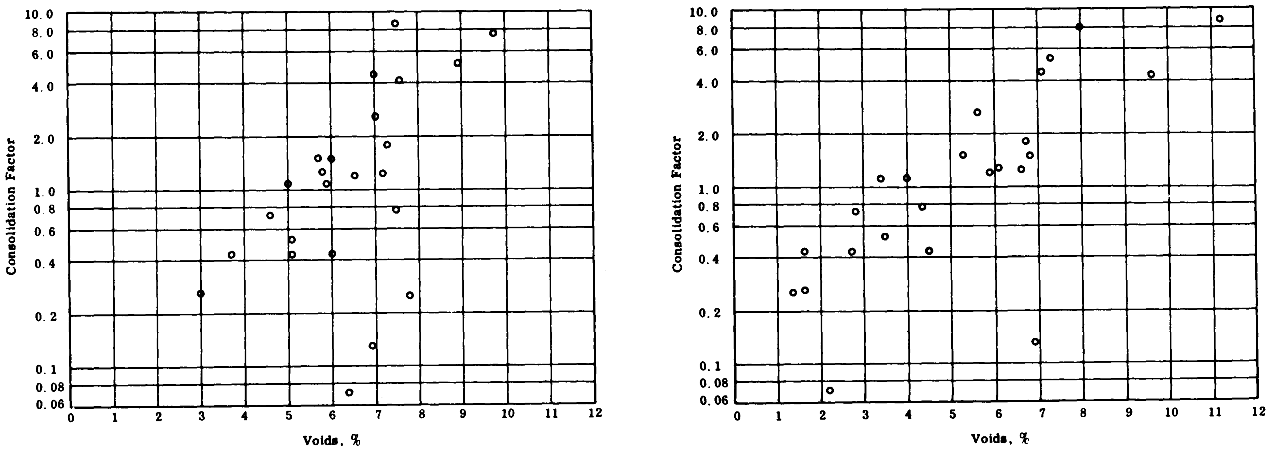
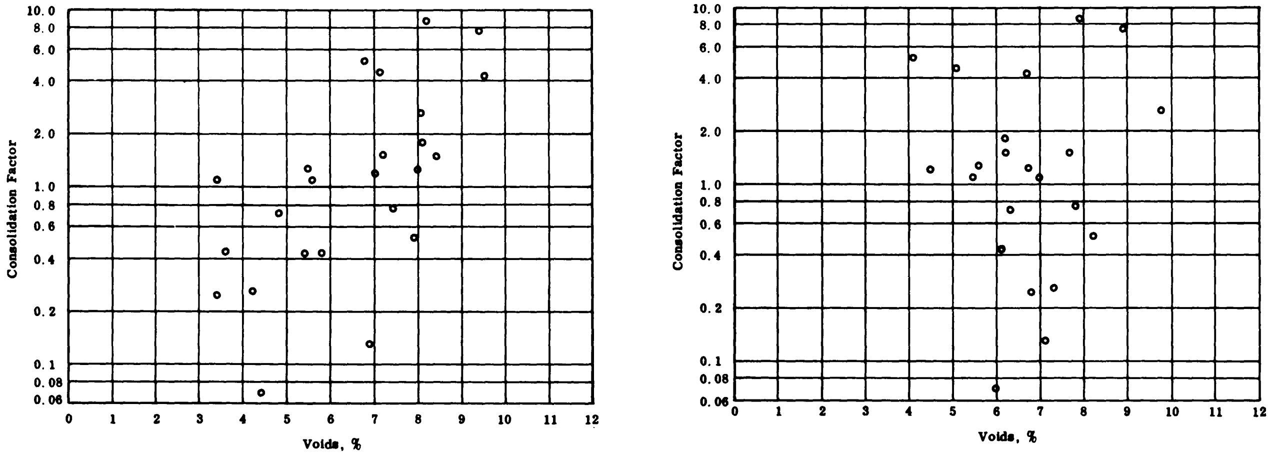


Figure 4b. Relationship between the consolidation factor and the voids of over 1mm diameter of the 24 core samples as measured by the linear traverse. (The curve shown is only an estimate.)



Slab 1

Slab 2



Slab 3

Slab 4

Figure 5. Relationship between the consolidation factor and the void content of the four individual levels of the 24 core samples as measured by the linear traverse method.

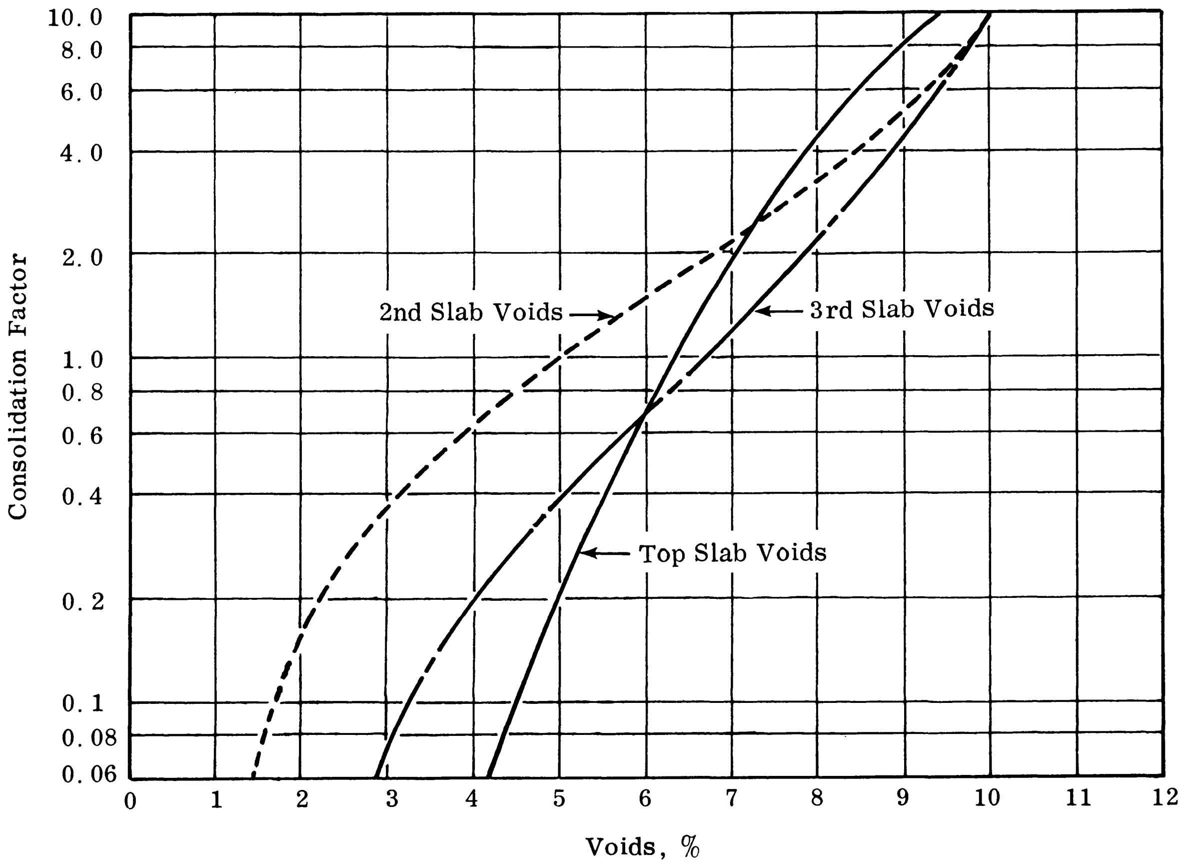


Figure 6. Comparison of the voids contents at the top three levels.

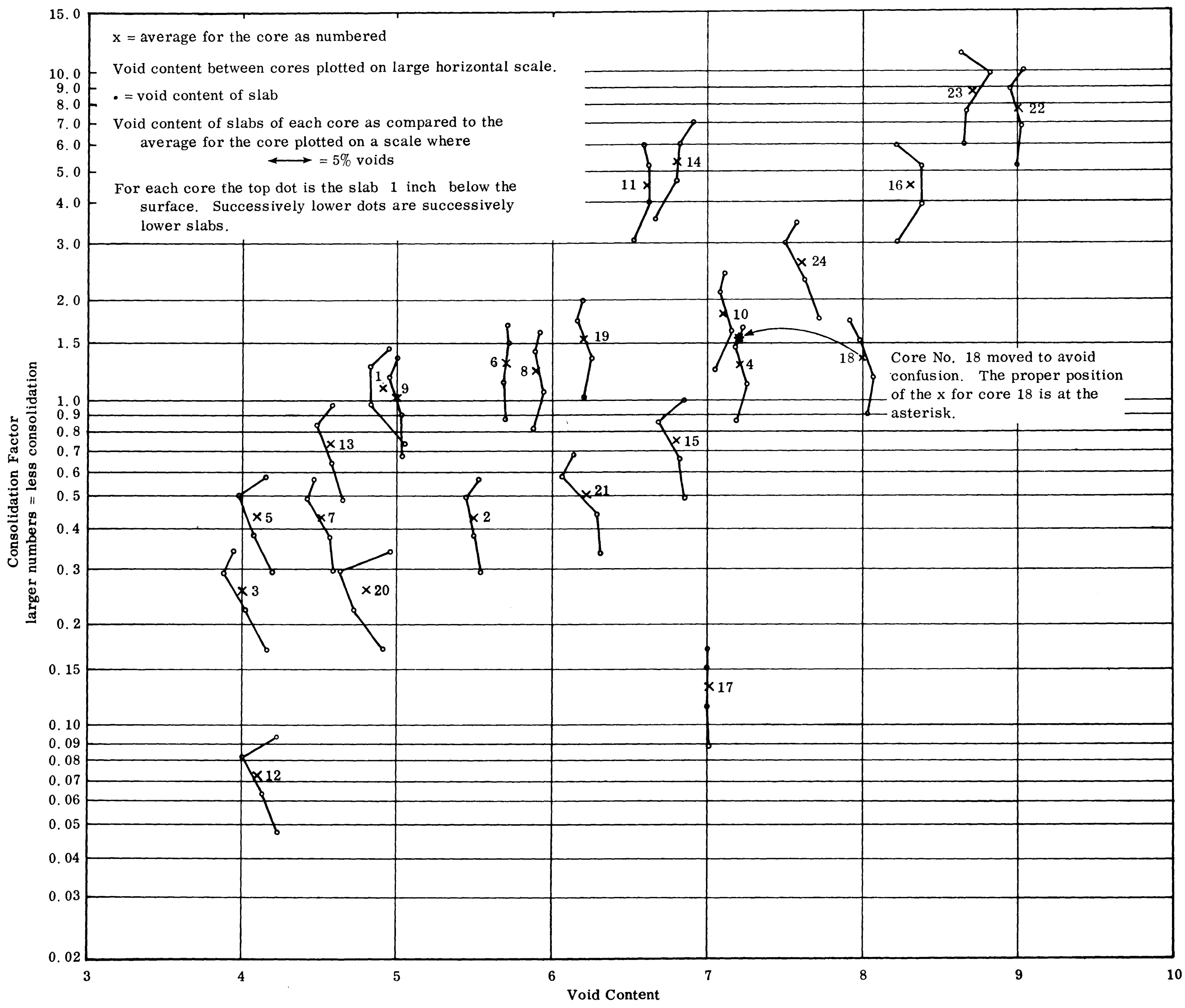


Figure 7. Change in void content with depth vs. consolidation factor.

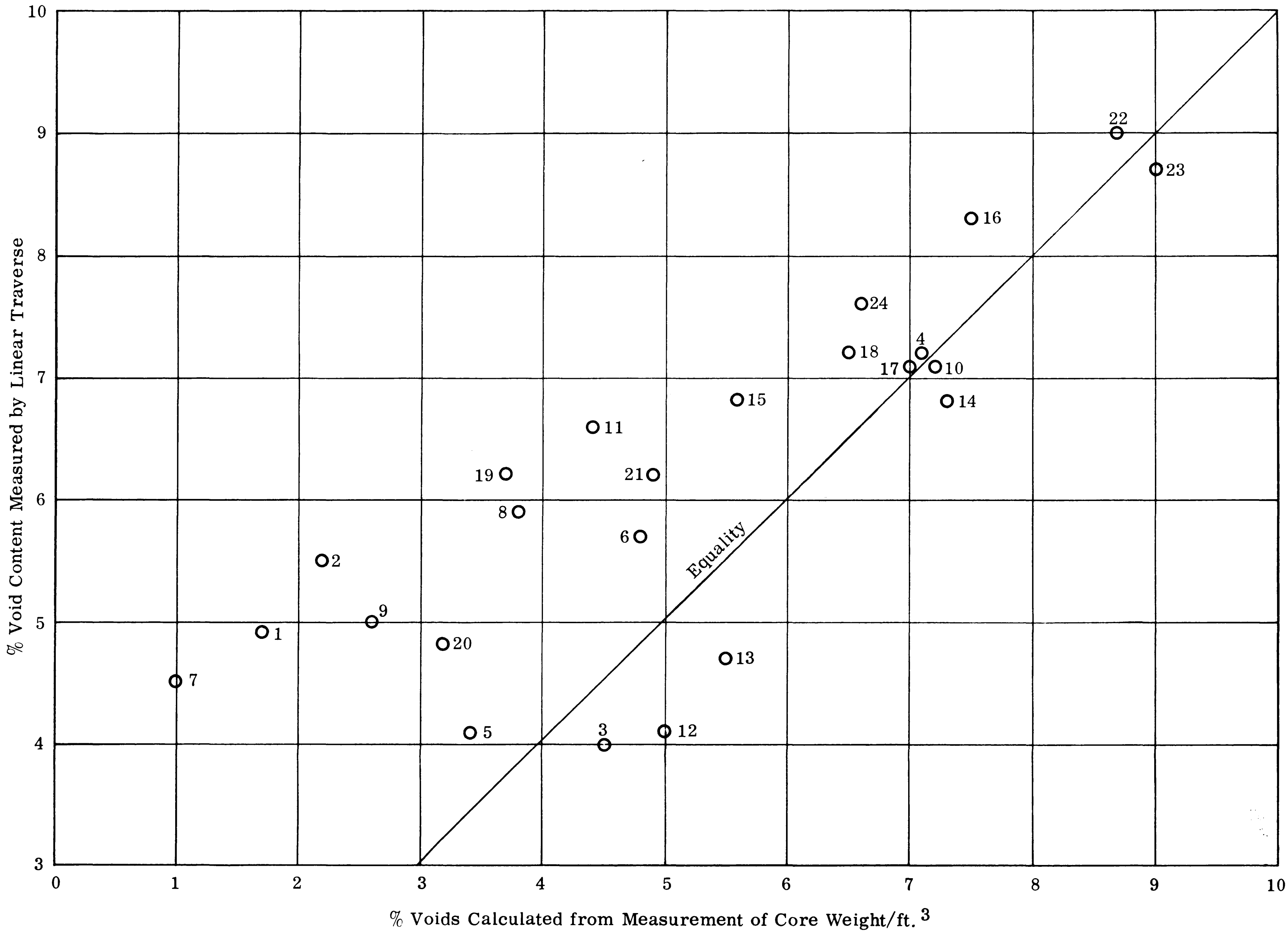


Figure 8. Comparison of void content measured on linear traverse with void content calculated from core weight/ft.^{3}

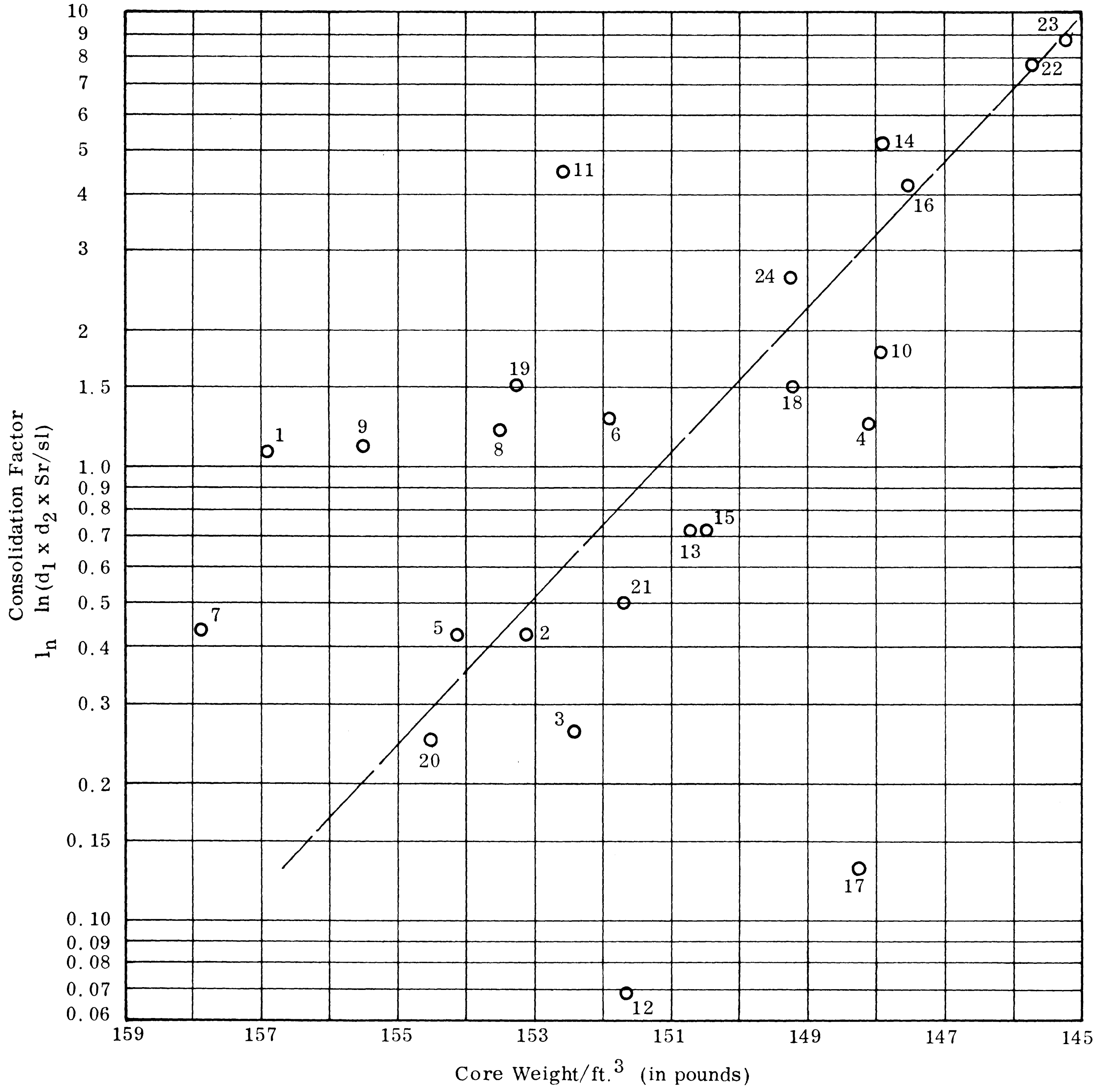


Figure 9. Core weight/ft.^{3} compared with consolidation factor.

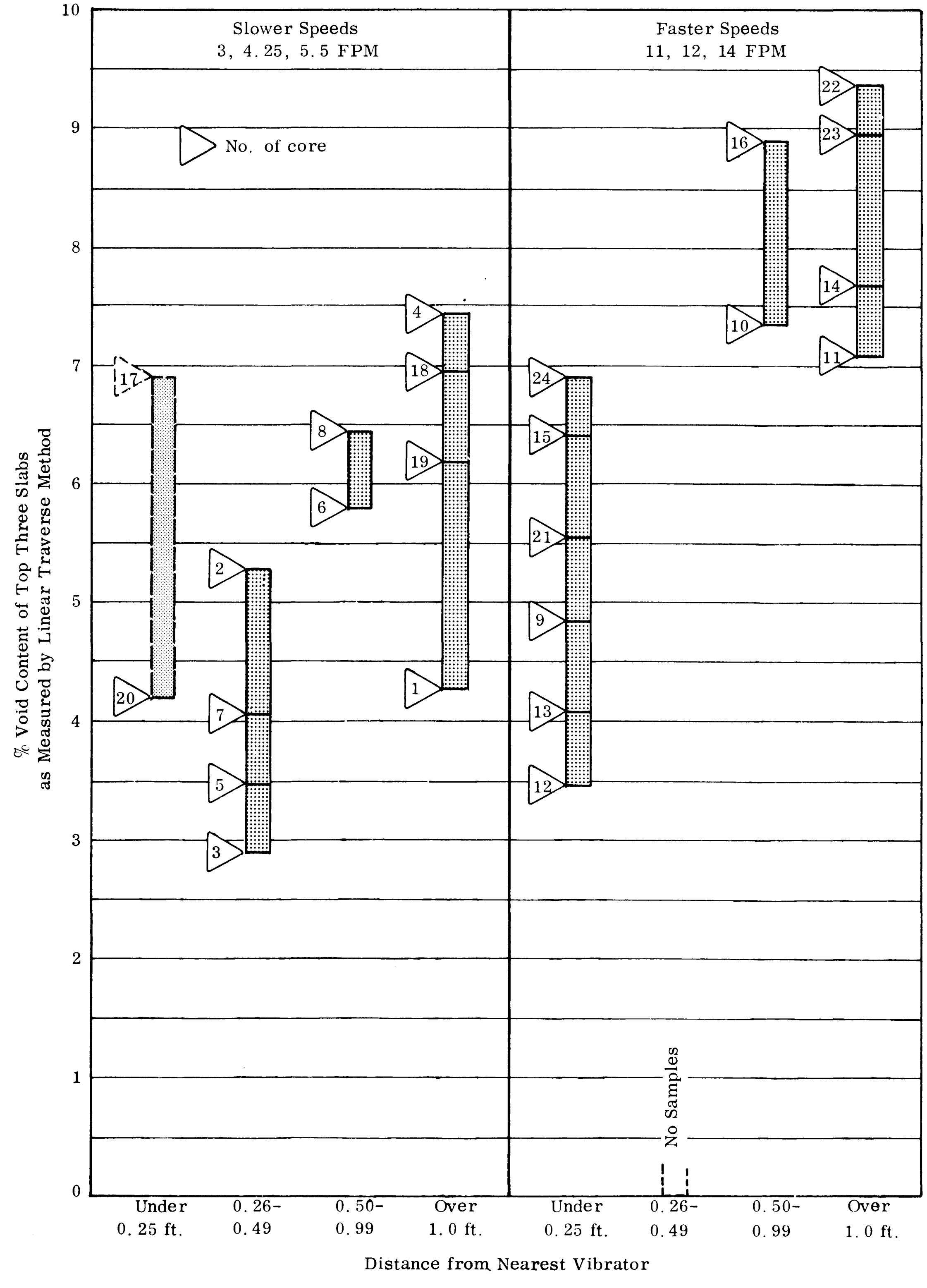


Figure 10. The effect of distance from the nearest vibrator and speed of paver on void content.

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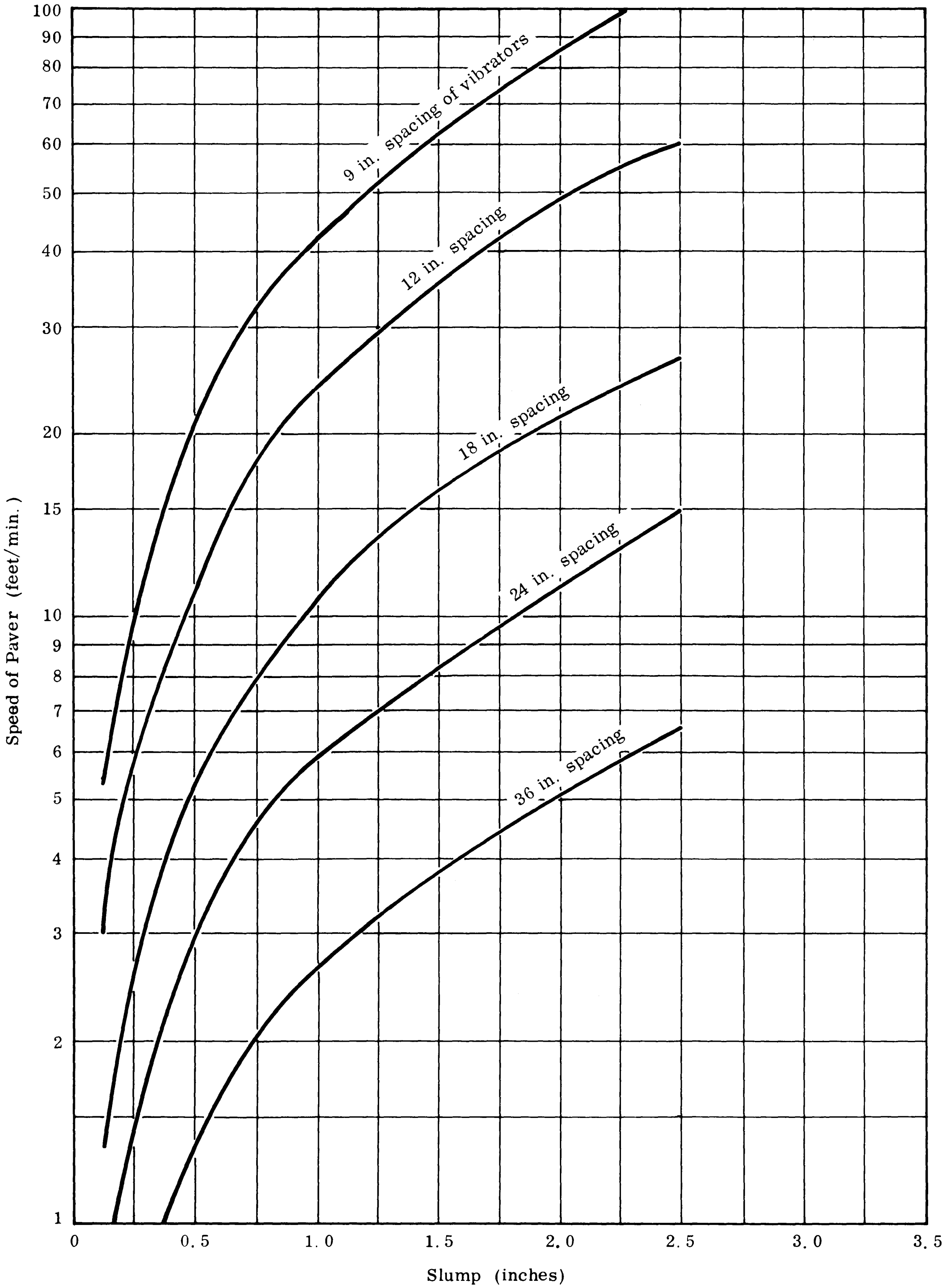

Figure 11. Hypothetical graph of speeds which should not be exceeded if consolidation factor is not to exceed 2.0.

TABLE 1

Hypothetical Table of Desirable Forward Speeds of Spreader, Consolidation Factor Between 0.2 and 2.0, For Slumps of 0.25 to 2.5 Inches and Spacings of 9 Inches to 36 Inches

Slump, Inches	Spacings, Inches	Range of Forward Speed, Feet per Minute		
		CF 0.2		CF 2.0
0.25	18	1.25	—	2.5
	12	2	—	6
	9	3	—	11
0.5	36	1.25	—	1.3
	24	2	—	3
	18	3	—	5
	12	4	—	12
	9	5	—	21
0.75	36	1.8	—	2.0
	24	3	—	4
	18	4	—	8
	12	6	—	18
	9	8	—	32
1	36	2.5	—	2.7
	24	4	—	6
	18	5	—	10
	12	8	—	24
2	36	5	—	5.3
	24	8	—	12
	18	10	—	21
	12	16	—	48
2.5	36	6.2	—	6.7
	24	9	—	15
	18	13	—	27
	12	20	—	60

APPENDIX

Tables from unpublished report entitled Vibrator Test
by Robert Bruce of the Ballenger Paving Co. , April 1970

RESULTS OF THE ANALYSES OF THE 24 CORES

Core No.	Pulse Velocity Ft./sec.	Young's Modulus P. S. I.	Unit Weight	Percent Air	Percent Voids	Steel in Cores
1	14,500	6,169,038	160.04	6.6	0.3	X
2	14,353	5,893,474	156.00	6.6	2.8	X
3	13,861	5,496,360	156.00	6.6	2.8	
4	13,802	5,295,960	151.63	6.6	5.5	X
5	14,402	5,983,231	157.25	6.5	1.9	
6	13,716	5,361,267	155.38	6.5	3.0	X
7	14,095	5,863,668	160.99	6.5		X
8	13,977	5,588,741	156.00	6.5	2.6	X
9	13,340	5,221,474	159.74	6.0		X
10	13,668	5,173,070	151.01	6.0	5.3	
11	13,612	5,300,568	156.00	6.0	2.2	X
12	14,063	5,612,318	154.75	6.0	3.0	
13	13,802	5,405,882	154.75	6.5	3.4	
14	14,130	5,551,629	151.63	6.5	5.4	
15	13,830	5,362,266	152.88	6.5	4.6	
16	13,000	4,679,951	151.01	6.5	5.7	
17	13,498	5,045,395	151.01	6.2	5.4	
18	13,235	4,890,896	152.26	6.2	4.7	
19	13,629	5,356,407	157.25	6.2	1.5	X
20	14,041	5,707,474	157.87	6.2	1.2	
21	14,009	5,591,971	155.38	7.6	4.2	X
22	13,498	5,003,631	149.76	7.6	7.6	
23	13,135	4,678,944	147.89	7.6	8.8	
24	13,387	5,003,873	152.26	7.6	6.1	

X — denotes steel in cores.

CHARLOTTESVILLE, VIRGINIA
Concrete Cores

Core No.	Avg. Length	Avg. Diameter	Core Vol., Cu. Ft.	Core Weight, Lbs.	Core Weight, Per Cu. Ft.
1	8.00	4.0256	.0589	9.24	156.88
2	7.75	4.0054	.0565	8.65	153.10
3	8.15	4.0096	.0596	9.08	152.35
4	7.95	4.0052	.0580	8.59	148.10
5	7.95	4.0082	.0580	8.94	154.14
6	7.90	4.0040	.0576	8.75	151.91
7	7.95	4.0078	.0580	9.16	157.93
8	8.05	4.0036	.0586	8.99	153.41
9	8.00	4.0086	.0584	9.07	155.31
10	8.20	4.0060	.0598	8.85	147.99
11	8.00	4.0082	.0584	8.91	152.57
12	8.10	4.0082	.0591	8.96	151.61
13	7.95	4.0096	.0581	8.76	150.77
14	7.85	4.0100	.0574	8.49	147.91
15	7.80	4.0114	.0570	8.58	150.53
16	7.80	4.0232	.0574	8.47	147.56
17	7.45	4.0138	.0546	8.09	148.17
18	8.10	4.0220	.0596	8.89	149.16
19	7.85	4.0214	.0577	8.86	153.55
20	7.75	4.0208	.0569	8.79	154.48
21	7.90	4.0244	.0581	8.81	151.64
22	7.45	4.0656	.0560	8.16	145.71
23	7.25	4.0592	.0543	7.88	145.12
24	7.55	4.0632	.0567	8.45	149.03