VOID PARAMETERS OF CONCRETE CORES FROM A SECTION OF I-64

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In the hope of determining whether variables in unit weight were caused by variations in the air void system or segregation of the aggregate, micrometric air void and aggregate analyses were made on 24 core samples from six test sections of I-64 near Charlottesville, Virginia. The test design included paver speeds of 3, 4.25, 5.5, 11, 12, and 14 ft/min (0.0152, 0.0261, 0.0279, 0.0559, 0.061, and 0.071 m/s), vibrator frequencies ranging from 130 to 167 revolutions/sec, and slumps from 1 to 2¾ in. (25.4 to 70 mm). Analyses showed that for any particular concrete, the faster the motion of the vibrators through the concrete and the greater the spacing, the less the consolidation will be. Between batches, the greater the slump or workability is, the greater the consolidation achieved by a set of vibrator conditions. 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. For the type of concrete and kind of vibrators used, data seem to indicate that, if the slump approaches 1 in. (25.4 mm), then the forward speed of the vibrator screed should be no more than 6 ft/min (0.0305 m/s) when the spacing of the vibrators is about 2 ft (0.61 m). Higher speeds will probably produce high-void, low abrasion-resistant areas of pavement.

• 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 that are irregular and greater than 1 mm in diameter are usually considered 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, well-consolidated concrete will provide high strength and high resistance to abrasion. Studies of four heavily traveled pavements in Colorado show 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, if the concrete is improperly proportioned, large amounts of consolidation can segregate the concrete and even remove enough of the purposely entrained air so that freeze-thaw resistance might be adversely affected.

Proper consolidation is, therefore, the densification effort that produces (a) concrete with a very low percentage of large voids (no honeycombs, "rat holes," or bleed channels); (b) the intended amount of entrained air; (c) an even distribution of the aggregate; and (d) the proportioned unit weight.

The factors that influence the degree of consolidation obtained by vibration include

1. Type of vibrator—size of head, frequency, amplitude, and force;
2. Spacing between vibrators;
3. Speed with which vibrators are moved through the concrete;
4. Workability of the mixture (slump);

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5. Aggregate—size, density, and grading; and
6. Amount of entrained air.

The effect of each of these factors and their interactions on each other have not been completely ascertained, although considerable insight has been gained by theoretical and experimental studies (1, 2, 3, 4, 5). Because of the complexities of these interactions, specifications for pavements are generally vague and contain statements such as good consolidation and proper vibration.

Air voids do not start to leave the concrete until a considerable amount of vibratory effort has been expended. Coarse voids can be almost completely removed; a certain portion of the fine voids cannot. As the vibration becomes more effective, the concrete is apt to become segregated. Mortar and, particularly, paste will probably move toward the vibrators, and coarse aggregate will probably move away from the vibrators and sink. The effect of the removal of voids is complex because resistance to freezing and thawing increases with increased entrained air although strength and resistance to abrasion decrease. Generally, the coarse 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 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 ft/min (0.0152, 0.0216, 0.0279, 0.0559, 0.061, and 0.071 m/s) and frequencies ranging from 130 to 167 revolutions/sec were used in six test sections (6). The pavement was 8-in.-thick (203 mm) continuously reinforced concrete (0.6 percent longitudinal steel, no transverse steel). The concrete design weight was 149.96 lb/ft^3 (2402.13 kg/m^3). Slip-form operations were used to place the pavement in a 24-ft (7.3 m) width. Four core samples were obtained from each test section.

The report of the experiment (6) discusses determinations of the modulus of elasticity by sonic methods and density determinations of the 24 cores. Figure 1 shows location of the samples relative to the path of the vibrators and the several paver speeds. Almost every core represented a unique combination of paver speed, distance from vibrator, slump, air content, etc., so that there is no replication of conditions among the samples. When the experiment was initiated, it was anticipated that the variations in vibration conditions would be reflected in the results of conventional density and derived void-content determinations.

Unit weights (6) indicated a large variation in void content across the pavement at a given station (Table 1). In the hope of determining whether the variation in unit weight was caused by variations in the air void system or segregation of the aggregate, the Virginia Highway Research Council was asked to make micrometric air void content and aggregate distribution 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 to produce a durable concrete pavement.

RESEARCH COUNCIL ANALYSES

Procedures

The 24 cores used were delivered to the Research Council laboratory. Each core was cut horizontally in four places to produce a 1-in.-thick (25.4 mm) top slab and three 1¼- to 2-in.-thick (32 to 51 mm) lower slabs. An effort was made to avoid cutting reinforcing steel. The underside of each slab was finished to a finely ground surface, and a linear traverse analysis of the void system was made using the procedures in ASTM C 457 (7). The largest aggregate size would pass a 2-in. (51 mm) mesh screen, and maximum cross sections occurred very rarely. Fifty inches (1270 mm) of traverse were examined on each slab. It was determined that the greatest variability in the void system was in the top two slabs—most particularly in the second slab—at about a 3½-in. (89 mm) depth and above. The top two slabs were etched in

Figure 1. Location of core samples.

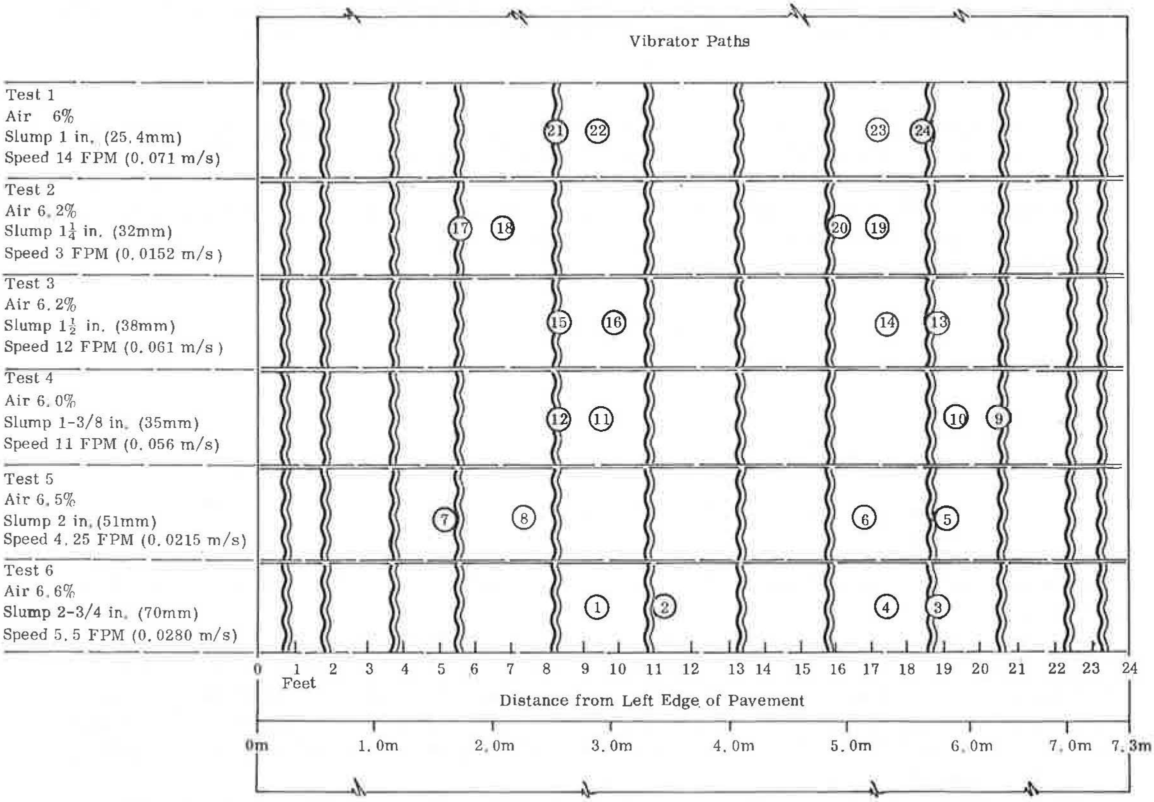


Table 1. Density measurements determined by weighing and measuring and derived void content of 24 cores.

Test No.	Core No.	Mass (lb/ft^3)	Derived Voids (percent)
1	21	151.64	5.2
	22	145.71	9.5
	23	145.12	9.9
	24	149.03	7.0
2	17	148.17	7.7
	18	149.16	7.0
	19	153.55	3.9
	20	154.48	3.3
3	13	150.77	5.8
	14	147.91	7.9
	15	150.53	6.0
	16	147.56	8.1
4	9	155.31	2.7
	10	147.99	7.8
	11	152.57	4.6
	12	151.61	5.2
5	5	154.14	3.5
	6	151.91	5.0
	7	157.93	1.0
	8	153.41	4.0
6	1	156.88	1.7
	2	153.10	4.2
	3	152.35	4.7
	4	148.10	7.7

Note: 1 lb/ft^3 = 16.01 846 kg/m^3.

0.3 N HCl for 20 sec, and the surfaces were subjected to a linear traverse analysis of the aggregate distribution. About 15 in. (380 mm) 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 related directly to the distances from the cores to the nearest vibrators, directly to the forward speed of the screed, and inversely to the slump. No relationship could be found between the frequency of the vibrators and void contents. Void content was plotted against a variety of expressions containing these variables. The best relationship was obtained by a factor of the form

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

where

CF = consolidation factor,
d_1 and d_2 = distances to nearest vibrators,
S_r = relative speed = $\frac{\text{test speed}}{3}$, and
sl = slump, in inches.

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

No theoretical basis for this factor is proposed nor havè precedents been found in research reports. For the remainder of the paper it will be designated the consolidation factor, which 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 2 shows the relationship between the consolidation factor and void contents of the cores as determined by micrometric analyses. Core sample 17 was removed from the pavement that had probably undergone vibration of an intensity indicated by a consolidation factor of 0.13. The 7 percent air voids may indicate a malfunction of the nearest vibrator.

Data from each level were plotted separately against the consolidation factor. The best correlation was found in the second level down, and none can be discerned in the fourth level. Data were extrapolated to provide curves for each of the top three levels (Fig. 3). There is a variation in void content vertically as well as laterally. The second level is the area most consolidated (containing least voids) for a given set of vibration parameters. Figure 4 shows the combined data for each core sample. In cores most exposed to the vibrators (those in the lower portion of the graph) the lowest void content is in the second slab [about 3½ in. (89 mm) from the surface].

Aggregate content data were analyzed by the same methods, but no correlation between void content and consolidation factor could be found. Because the effect of vibration on void content was most noticeable at the 3½-in. (89 mm) depth, the aggregate content at this level was studied separately. No correlation between aggregate content and any vibration parameter was found. Only 15 in. (381 mm) of linear distance were examined on a 4-in.-diameter (102 mm) surface, and it may be that the scatter of these data and lack of correlations merely indicate insufficient sampling.

DISCUSSION

The best correlation between unit weight and Bruce's void data (6) and void content data obtained by linear traverse at the Research Council was arrived at by (a) comparing the specified unit weight with unit weights as measured by the simple weighing and measuring procedure, (b) calculating the indicated percentages of voids, and (c) plotting

Figure 2. Relationship between consolidation factor and void content.

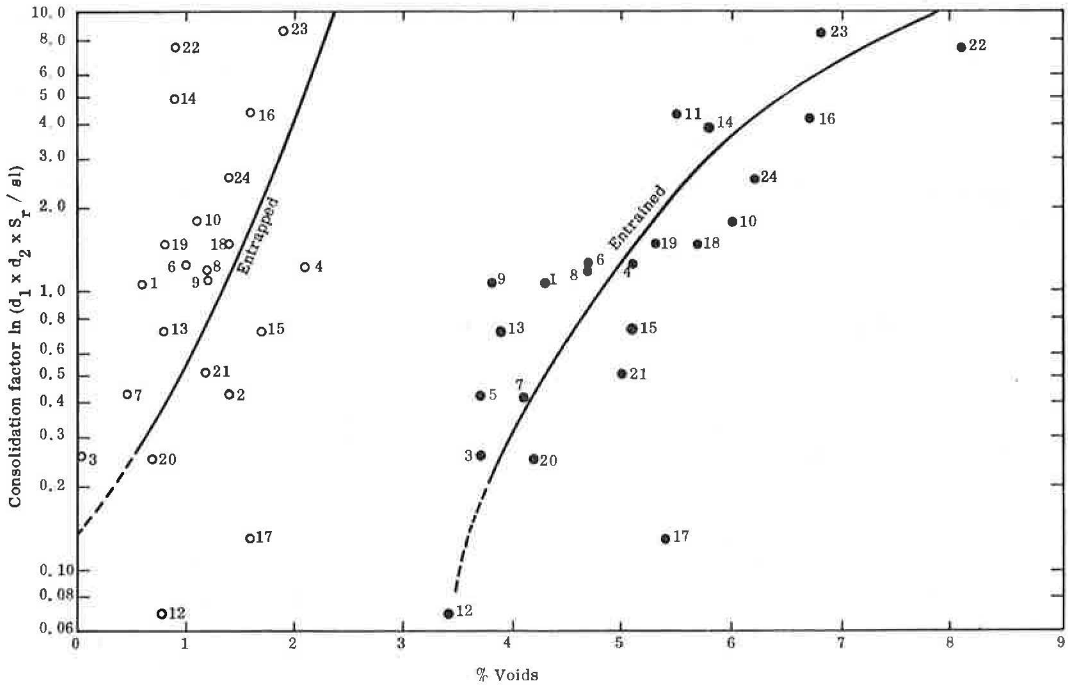


Figure 3. Extrapolation of total void content as determined by linear traverse measurement.

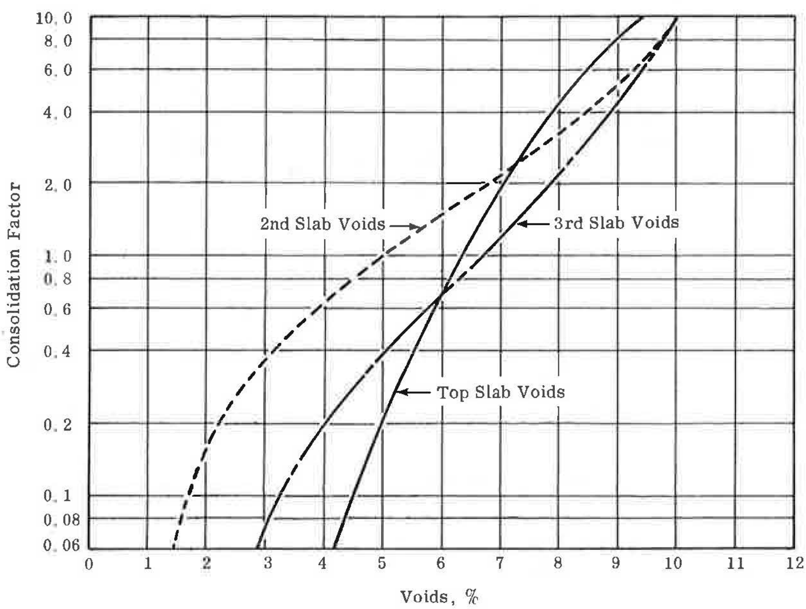
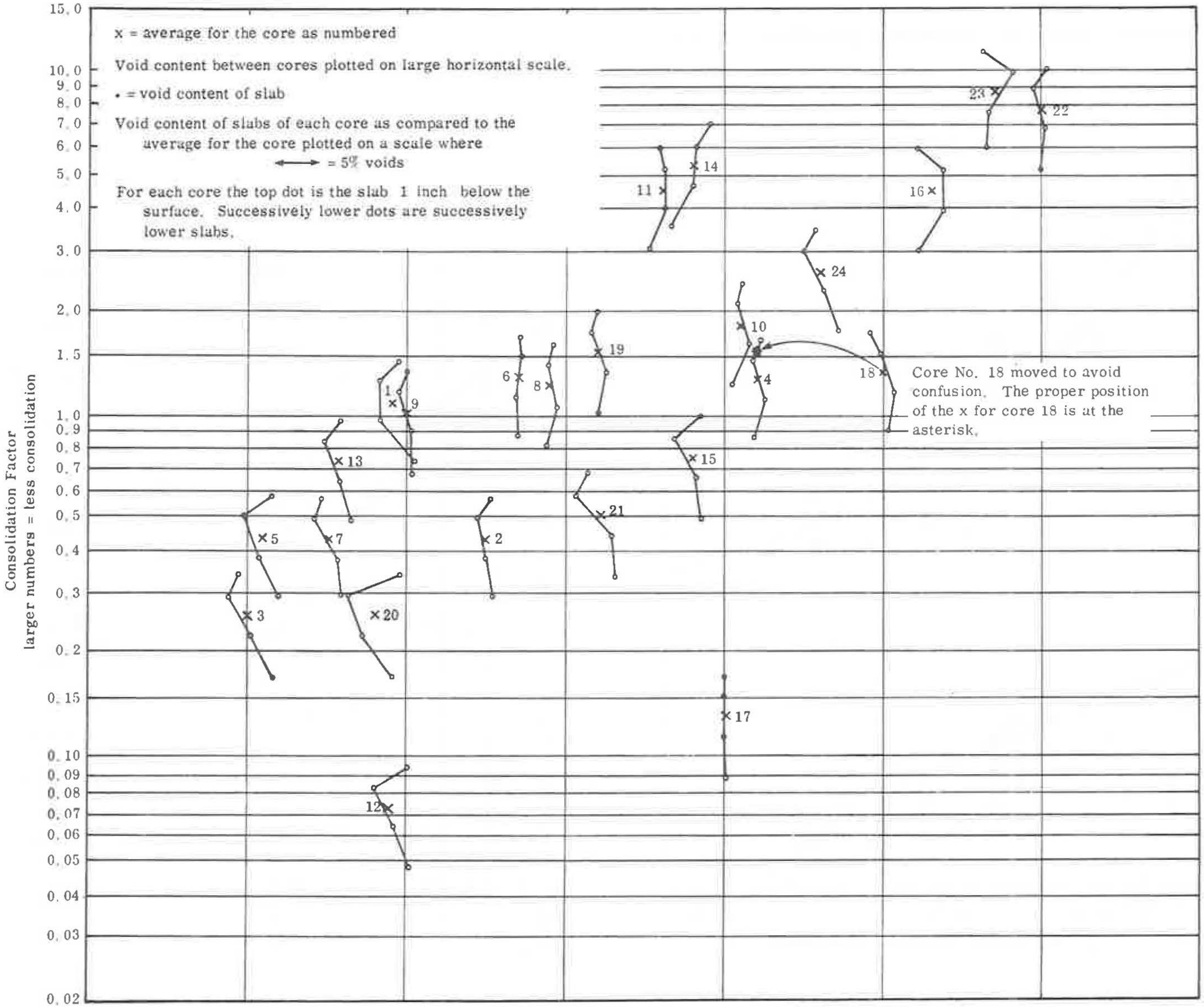


Figure 4. Relationship between total consolidation of the core and vertical distribution of voids within the core versus the consolidation factor.



them against the voids measured by the linear traverse. Figure 5 shows these data. Void contents over 7 percent showed excellent correlation. Many of the cores with less than 7 percent voids had weights that were high in respect to their void content. This may have been caused by aggregate concentrations. The two worst discrepancies were with cores 1 and 7, which are among the cores with higher coarse aggregate contents. However, cores 22 and 17 have equally high coarse aggregate contents but show little discrepancy between measured void content and calculated void content. Perhaps the aggregate content data are faulty because of insufficient sampling. The steel in the cores showed no consistent effect.

More intensive testing, designed according to statistical theory and including core samples of replicate conditions, would provide defensible answers of more quantitative precision than those from this study. However, such a program would be quite costly. If the precision now obtained in the determination of the segregation of total voids were required for the coarse aggregate and for voids over 1 mm in diameter, it is estimated that 12 times as much surface area of concrete would have to be examined for each sample. If twice as much prepared surface were produced and analyzed on each core, six 4-in. (102 mm) cores would be required per sample. If variables in this intensive testing program were limited by keeping slump and vibration constant and including only two paver speeds, three spacings of vibrators, three distances of samples from the vibrator, and only one replication, 216 cores would be required. Although a study of this design would permit quantitative conclusions, it is doubtful that generalizations pertaining to conditions other than those in the study would be valid. The trends obtained from this study appear reasonable and valid, and whether refinement is warranted is a matter for debate. Thus, the study results are helpful in establishing general relationships and trends (in numerical form) concerning the order of magnitude of the interactions of the factors involved in the consolidation process.

Hypothetically, if curves drawn from sufficient data approximate the curves shown in this paper, and if the consolidation factor used here has the appropriate formula for experimental conditions, then, by examination of Figure 2, one might conclude that (a) nearly all of the large diameter voids are driven out at a factor of 0.2; (b) sufficient large voids are removed at 2.0; and, therefore, (c) a desirable consolidation factor would be between 0.2 and 2.0. As a result, one might want to construct a graph as shown in Figure 6.

The consolidation factor discussed here does not take into account the finite limit of the range of effectiveness of vibrators. The radius of this limit is unknown, but it is 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 vibrator spacings of more than 36 in. (0.91 m).

CONCLUSIONS

Research Council data confirm that, for any particular concrete, the faster the motion of the vibrators through the concrete and the greater the spacing, the less the consolidation will be. Between batches, the greater the slump or workability is, the greater the consolidation achieved by a set of vibrator conditions will be. 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 and for slumps approaching 1 in. (25.4 mm) and vibrator spacings of 2 ft (0.61 m), the data seem to indicate that the forward speed of the vibrator screed should be no more than 6 ft/min (0.0305 m/s); otherwise high-void, low-abrasion-resistant areas will result. For faster speeds, the spacing between vibrators should be decreased. Vibratory methods much in excess of those lowering the consolidation factor to 0.2 would not be economically practical and might, in a poorly designed mix, lower the air content of the concrete below that needed to prevent freeze-thaw damage.

Figure 5. Relationship between void content calculated from core weight per cubic foot and void content determined micrometrically.

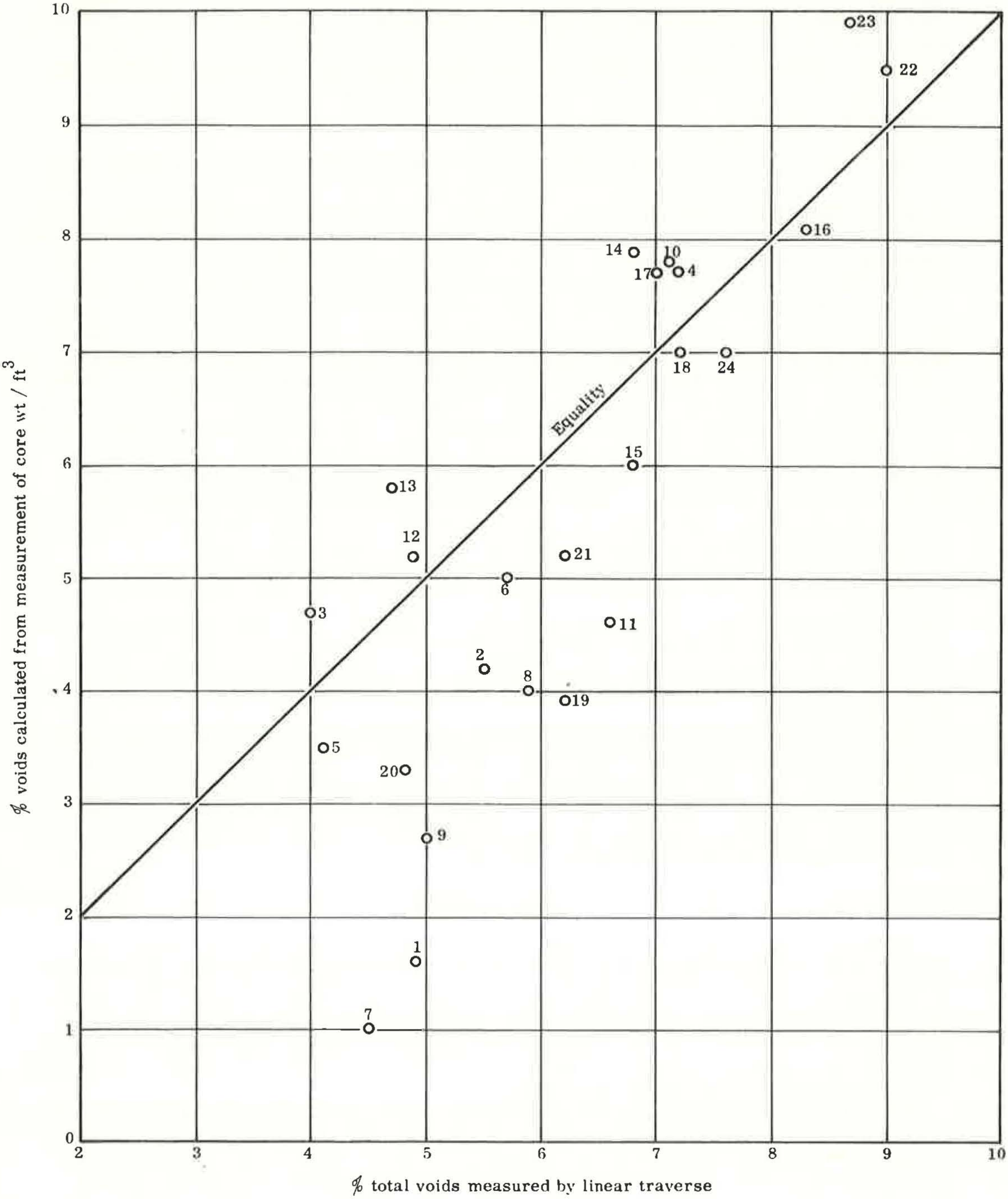
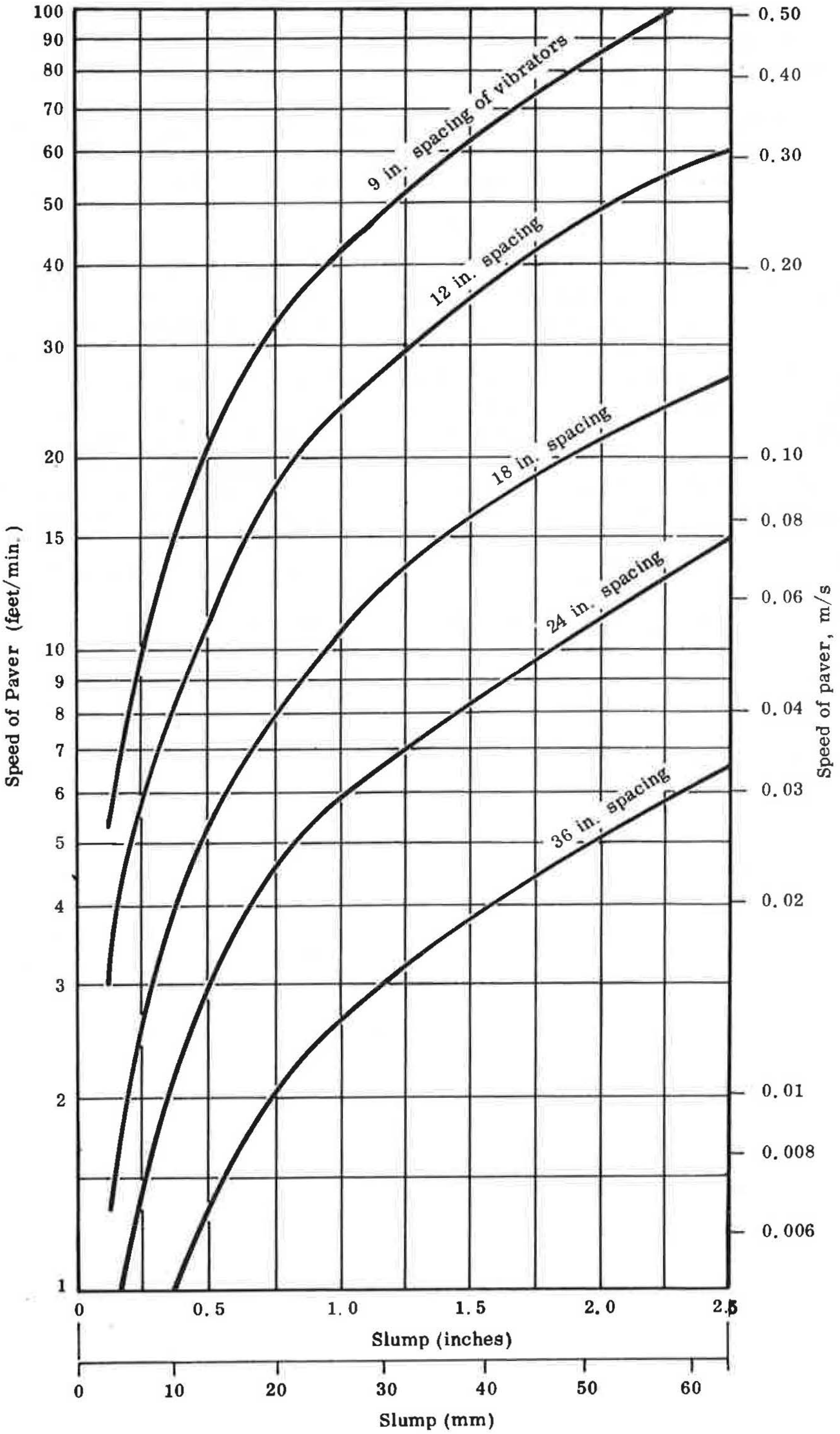


Figure 6. Hypothetical graph of paver speeds.



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