THE VOID SPACING INDICATOR

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Air Entrainment in Concrete

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The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the Texas Highway Department or the Bureau of Public Roads.

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Introduction

In 1945, T. C. Powers[1] showed that increased frost resistance of air-entrained concrete was largely a result of the size and spacing of air voids in the cement paste. By considering the hydraulic pressures which may accompany the freezing process, he proposed that the maximum average distance from a point in the paste to the nearest air void be no greater than about .01 inches. To indicate this distance, Powers introduced the spacing factor, $\overline{L}$.

Mielenz[2] and others[3,4,5] later found that frost resistance of concrete was greatly improved when the value of the spacing factor was about .008 inches or less as illustrated in Figure 1.

This spacing factor must be determined on hardened concrete and requires the use of elaborate equipment including a linear traverse device meeting the specifications of ASTM C-457. The purpose of the test described in this report is to give an indication of the spacing factor in plastic concrete using a simple device suitable for field testing. This would make possible the immediate detection of concrete susceptible to early failure under the disruptive forces caused by freezing and thawing.

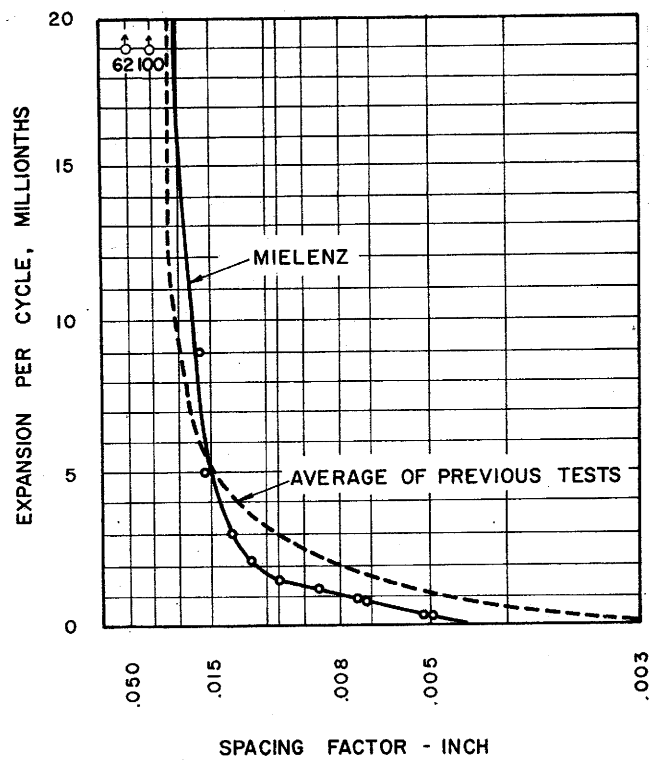

Figure 1. Spacing factor (from Reference 2).

Test Method

By exposing the entrained air bubbles of fresh concrete to visual observation, this new test provides a method for approximating the spacing factor of the air void system. This is accomplished by immersing a sample of mortar from the fresh concrete in a closed container completely filled with distilled water. As the mortar disperses in the distilled water, the entrained air bubbles are released and collect against the flat glass plate at the top of the container. The container developed for use in this test is shown in Figure 2. Figure 3 shows the bubbles after they have collected against the top of the container.

The total surface area of all the bubbles collected against the glass plate may be written as

$$S_T = 4\pi\,[r_1^2n_1 + r_2^2n_2 + \ldots r_i^2n_i], \qquad (1)$$

where n_i bubbles have a radius of r_i.

The total cross-sectional area of all the exposed bubbles is

$$\overline{a} = \pi\,[r_1^2n_1 + r_2^2n_2 + \ldots r_i^2n_i]. \qquad (2)$$

From equations (1) and (2), the total surface area of the bubbles may be written as

$$S_T = 4\overline{a}. \qquad (3)$$

The specific surface area of the system of bubbles is defined as

$$\overline{\alpha} = \frac{S_T}{V_T}, \qquad (4)$$

where V_T is the total volume of all the bubbles.

From equation (3), the specific surface area may be written as

$$\overline{\alpha} = \frac{4\overline{a}}{V_T}. \qquad (5)$$

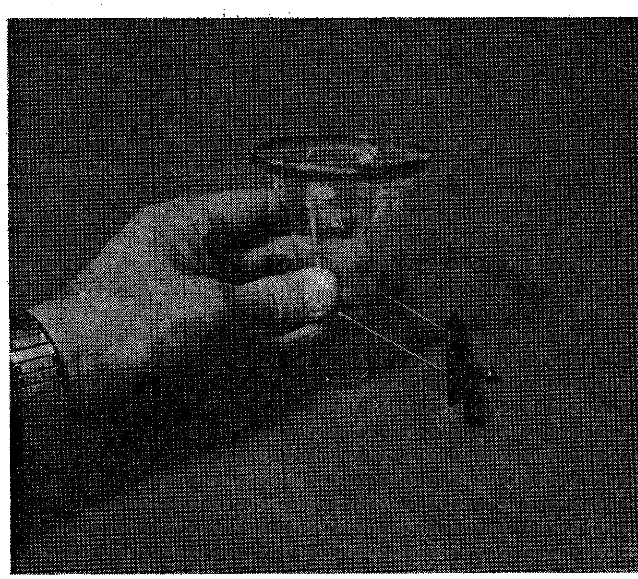

Figure 2. Container used in test.

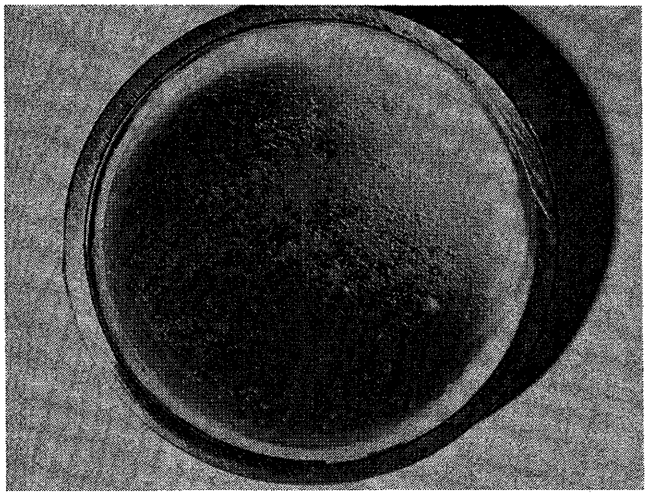

Figure 3. View of glass plate showing bubbles collected against top of container.

V_T for a given sample of concrete or mortar can be obtained by standard methods such as ASTM C-231 or the Chace Indicator.

The value of $\bar{a}$ for all the bubbles contained in a 0.212 in^3 sample of mortar is determined by estimating the area of the glass plate covered by the bubbles. It is then necessary to put the amount of air, V_T, in the 0.212 in^3 mortar sample into equation (5) to determine $\bar{\alpha}$. If A is the decimal fraction of air in the concrete as determined by ASTM C-231, then the amount of air in a 0.212 in^3 sample of *mortar* from this concrete is given by

$$V_T = 0.212 \frac{1}{(1-V_{CA})} A, \tag{6}$$

where V_{CA} is the volume of coarse aggregate, in cubic feet, per one cubic foot of concrete.

The equation for $\bar{\alpha}$, in terms of $\bar{a}$ becomes

$$\bar{\alpha} = \frac{4\,\bar{a}\,(1 - V_{CA})}{.212\ A}. \tag{7}$$

The spacing factor as determined by ASTM C-457 is given by equation (8) or (9).

$$\bar{L} = \frac{P}{\alpha A} \text{ for } \frac{P}{A} < 4.33. \tag{8}$$

$$\bar{L} = \frac{3}{\alpha} [1.4\,(P/A + 1)^{1/3} - 1] \text{ for } P/A > 4.33. \tag{9}$$

Where: α = the specific surface area of the air voids in hardened concrete, expressed as square inches per cubic inch of air void volume.

P = the proportional volume of cement paste in concrete expressed as a decimal fraction of the volume of the hardened concrete, calculated as the simple summation of the proportional volumes of the cement and water included in the concrete mixture.

A = the proportional volume of air voids in concrete, expressed as a decimal fraction of the volume of the hardened concrete.

Substituting the value of the specific surface area obtained from equation (7) into equations (8) and (9), the expressions for the void spacing factor in the fresh concrete, $\bar{V}$, is given by equations (10) and (11).

$$\bar{V} = \frac{0.053\ P}{\bar{a}\,(1-V_{CA})} \text{ for } P/A < 4.33. \tag{10}$$

$$\bar{V} = \frac{.159\ A}{\bar{a}\,(1-V_{CA})} [1.4(P/A + 1)^{1/3} - 1] \text{ for } P/A > 4.33. \tag{11}$$

Where: $\bar{a}$ = the area of the glass plate covered by bubbles, expressed in square inches.

A = the volume of air in the fresh concrete expressed as a decimal fraction.

P = the proportional volume of cement paste in concrete expressed as a decimal fraction of the volume of the hardened concrete, calculated as the simple summation of the proportional volumes of the cement and water included in the concrete mixture.

The detailed procedure for performing this test is given in Appendix A.

The value of $\bar{a}$ determined by the VSI test is at best an approximation. Several assumptions and known sources of error are involved, which will be briefly discussed.

1. It is assumed that the coalescence of the bubbles is negligible, and that the bubbles which cover the view plate are unchanged in geometry by the transition from the concrete into the mortar sample container and from this container through the water to the view plate. Observations of these tests have indicated a very small tendency toward coalescence of bubbles in the water media over the time interval necessary for the test.

2. The area between bubbles in the closely packed condition is not deducted.

3. There is always some stacking of the smaller bubbles below the layer of bubbles adjacent to the view plate, although the test procedures tend to minimize this effect.

It should be noted that these last two sources of error tend to be compensating.

Test Results and Discussion

These test results were obtained in both the field and laboratory using concrete samples taken during three phases of a study on air entrainment.[6]

During the Field Survey phase, 30 samples were taken during the construction of three bridge decks. From the Ready Mix phase, 36 samples were obtained from 7-yard ready mix concrete trucks while the laboratory phase provided 36 samples from 2-cubic-foot batches.

The air content of each sample was determined in accordance with ASTM C-231 when a Void Spacing Indicator (VSI) test was performed.* Two 3- x 3- x 16-inch beams were cast from each sample: one for microscopic determination of the spacing factor in the hardened concrete (ASTM C-457) and the other for determining the freeze-thaw durability factor (ASTM C-290).

The properties of all concrete batches sampled in each of the three phases of this program are given in Appendix B.

*VSI spacing factors ($\bar{V}$) for the laboratory and ready mix programs are the average of three determinations while those of the field survey program were determined from a single observation.

Figure 4 shows the VSI spacing factor ($\bar{V}$) compared to freeze-thaw durability for all concretes mixed in ready mix trucks. This includes both the Ready Mix and the Field Survey concrete data. For VSI spacing factors below .0120, high durability factors are shown; while above .0120 low durability factors are found.

Differences in the VSI spacing factors, ($\bar{V}$), were noted between the Laboratory concrete batches and the Ready Mix and Field Survey concrete batches. Among the Field Survey batches, the average ratio of VSI spacing factor to Powers' spacing factor, $\bar{V}/\bar{L}$, was 1.66. In the case of the Ready Mix batches this average ratio decreased to a value of .94. The reason for this becomes obvious when the decrease of air content from the plastic to the hardened concrete is considered (see Tables 1-B and 2-B). In the Ready Mix batches $\bar{V}$ was determined on the plastic concrete which had an average air content of 5.47%. $\bar{L}$ was then determined on the hardened concrete which had an average air content of only 3.48% (an average reduction of 1.99%). This decrease of air content causes a higher value of $\bar{L}$, resulting in a reduced ratio of $\bar{V}/\bar{L}$. This reduction in air content also influenced the values of $\bar{V}/\bar{L}$ determined in the Field Survey, where the average air content of the

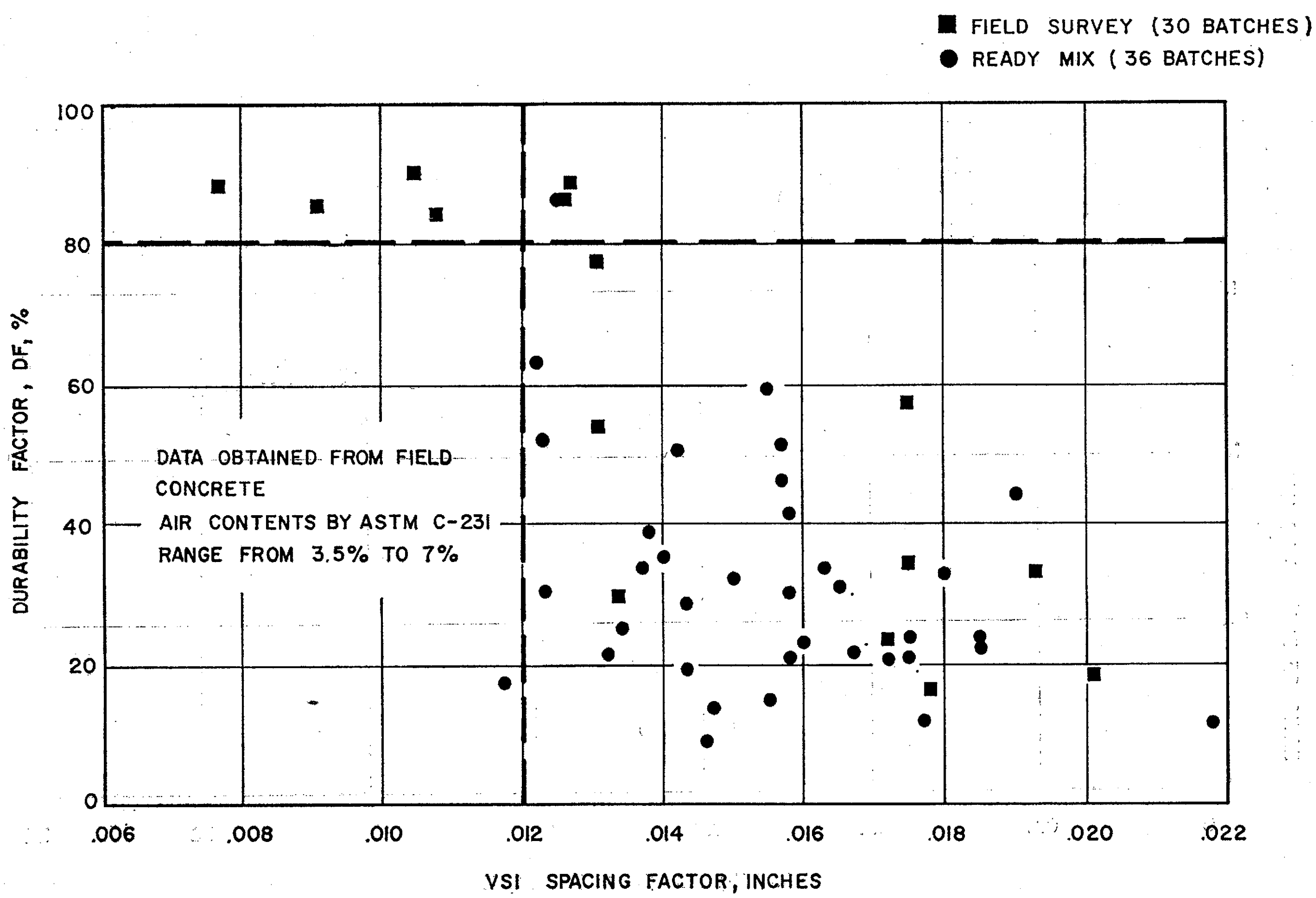

Figure 4. Comparison of VSI with frost resistance.

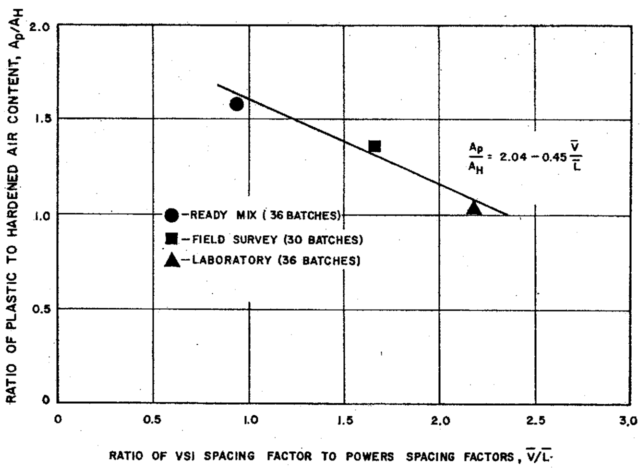

Figure 5. Variation of $\overline{V}/\overline{L}$ with A_p/A_H.

plastic concretes was 5.40% as compared to the average air content of 3.94% after hardening (an average reduction of 1.46%).

The values of $\overline{V}$ determined on the Laboratory batches were considerably larger than the values determined for $\overline{L}$. The average ratio of $\overline{V}/\overline{L}$ was 2.18 for these concretes. In this case there was almost negligible reduction of air content from the plastic to the hardened state (5.55% to 5.40%), so that this effect on the values of $\overline{V}/\overline{L}$ should have been minimal. It appears that this increase in the average ratio of $\overline{V}$ to $\overline{L}$ can be attributed to the relatively small difference in air content from the plastic to the hardened state. This variation in the ratio of $\overline{V}$ to $\overline{L}$ is shown in Figure 5 as a function of the ratio of pressure meter air content to hardened air content (A_p/A_H). If future investigations show that Figure 5 accurately describes this relationship, it may be possible to calibrate the VSI to predict values of $\overline{L}$ in the hardened concrete for a given project, with a series of determinations of air content on both the plastic and hardened concrete. Such a calibration could be applied as a modifying coefficient in the $\overline{V}$ equation. The data that are presently available indicate that this coefficient has a fairly linear variation with the A_p/A_H ratio. Using the method of least squares to fit a line to the points shown in Figure 5, this modifying coefficient, K, can be related to the A_p/A_H ratio. This relationship is shown in Figure 6.

It is recommended that a single VSI reading not be used as an indication of spacing factor. The test shows considerable variability (average CV for within batch tests on Ready Mix concrete was 21%), thus showing that multiple tests must be used to indicate the VSI spacing factor. This does not mean that a series of single tests is not a useful indicator for quality control purposes, but that repeated tests must be run for a reliable estimate of the VSI spacing factor.

For running quality control checks on concrete with constant proportions, an experienced inspector should be able to pick up changes in the quality of the air system by visual examination of the VSI view plate.

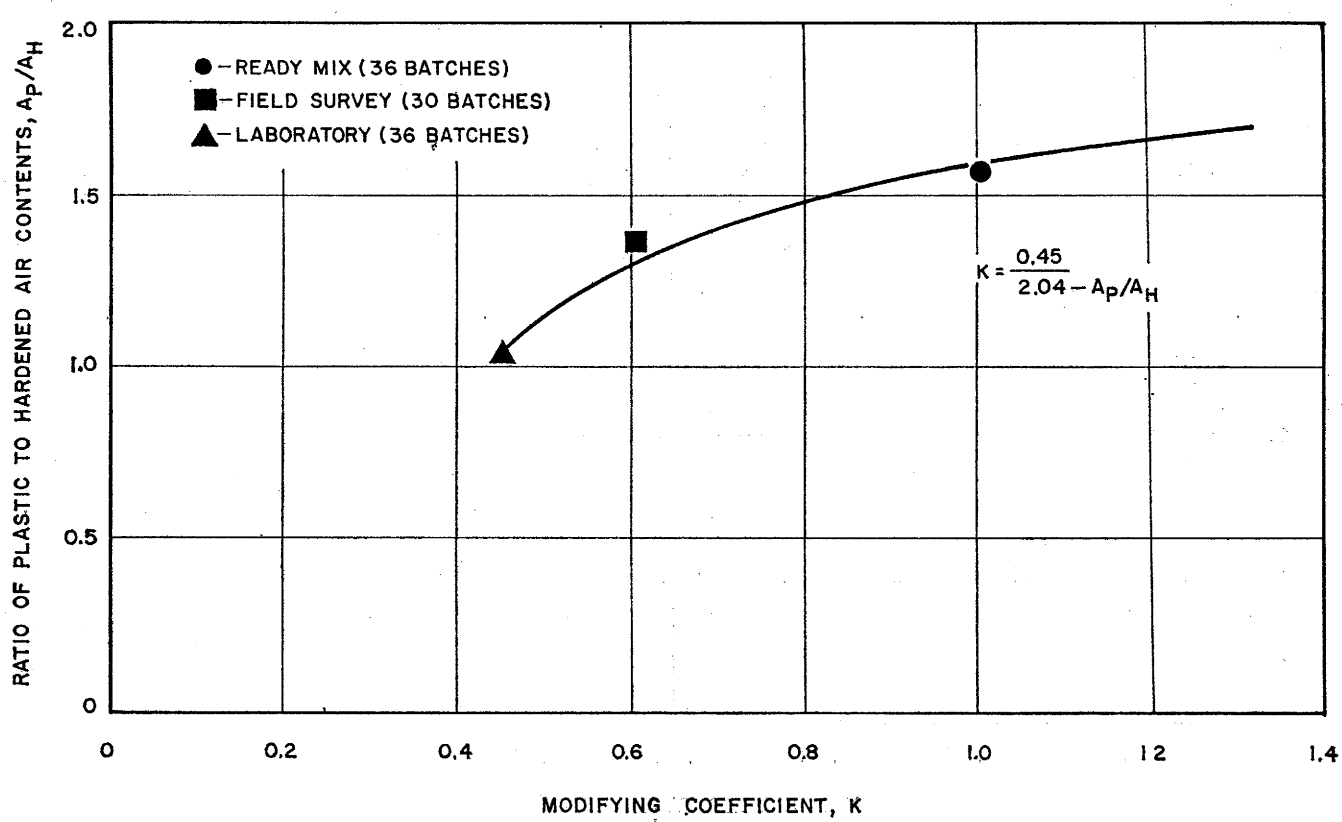

Figure 6. Variation of K with A_p/A_H.

The data which have been developed in this study are not sufficient to fully evaluate the Void Spacing Indicator. It is recommended that, if the test is to be used to determine actual values, as opposed to relative values of void spacing factor, it should first be correlated with determinations of Powers' spacing factor for the particular concrete involved.

This report contains the necessary information to use the Void Spacing Indicator to indicate a Powers Spacing Factor for concrete. It is not necessary, however, to use the VSI in this manner as a quality control device. Two other approaches to the use of this test for quality control are feasible. (1) The bubble system observed in the field can be compared to standard photographs of bubble systems which range in quality from excellent to poor. (2) If the proportions of the concrete mixes used on a particular job remain relatively constant, it is possible to dimension the view plate of the VSI so that any bubble system which does not cover the view plate is inadequate. As long as the view plate is completely covered by the bubble system, the system is adequate. This latter method is rather crude, but is probably the easiest to apply in the field.

Selected References

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2. Backstrom, J. E., Burrows, R. W., Mielenz, R. C., Wolkodoff, V. E., "Origin, Evolution, and Efffects of the Air Void System in Concrete. Part 2—Influence of Type and Amount of Air Entraining Agent," *Proceedings*, American Concrete Institute, Vol. 55, 1958, pp. 261-272.

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Appendix A

Test

VOID SPACING FACTOR OF FRESH CONCRETE
Equipment: Planimeter and equipment as shown in Figure 1-A.

Procedure:

1. Using a small spatula as shown in Figure 1-A, mortar is taken from the concrete and placed in the brass cup. Care should be taken to exclude aggregate particles larger than about ⅛″ in diameter.

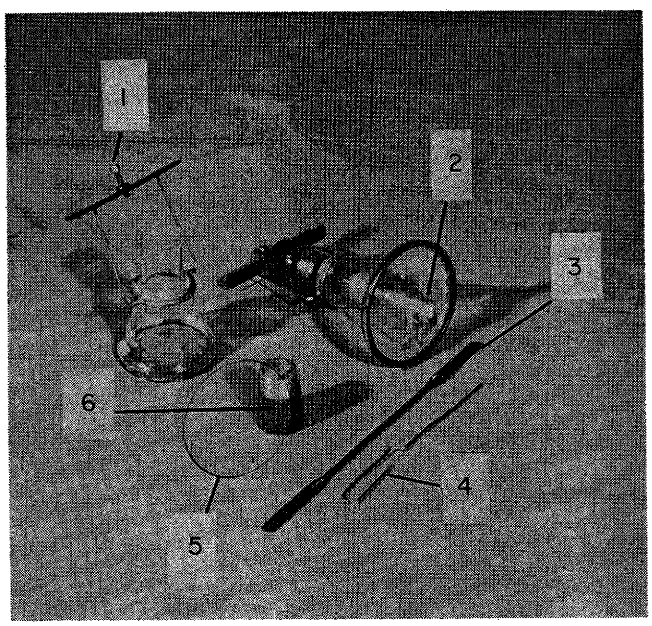
Fill the brass cup in two layers and rod each layer 20 times with a wire rod approximately 6 inches long and .05 inch in diameter. A straightened 2-inch size paper clip is ideal for this purpose.

After the second layer is rodded, strike off excess mortar even with the top of the cup.

2. Completely fill the glass container with distilled water and free any air bubbles adhering to the glass surfaces. Insert the cup and stopper into the filled container taking care that no air is introduced.

3. Secure the cup and stopper in the container by advancing the screw shown in Figure 1-A until contact is made with the rubber stopper; then, advance the screw one additional turn.

4. When the cup is first inserted in the container, very few air bubbles escape from the mortar. It is possible at this time to determine if air has inadvertently been introduced by inverting the container and observing the glass plate.



1. *Screw.*
2. *Glass plate.*
3. *Spatula.*
4. *Paper clip.*
5. *Transparent disc.*
6. *Brass cup with rubber stopper.*

Figure 1-A. Apparatus used in determining the void spacing factor in fresh concrete.

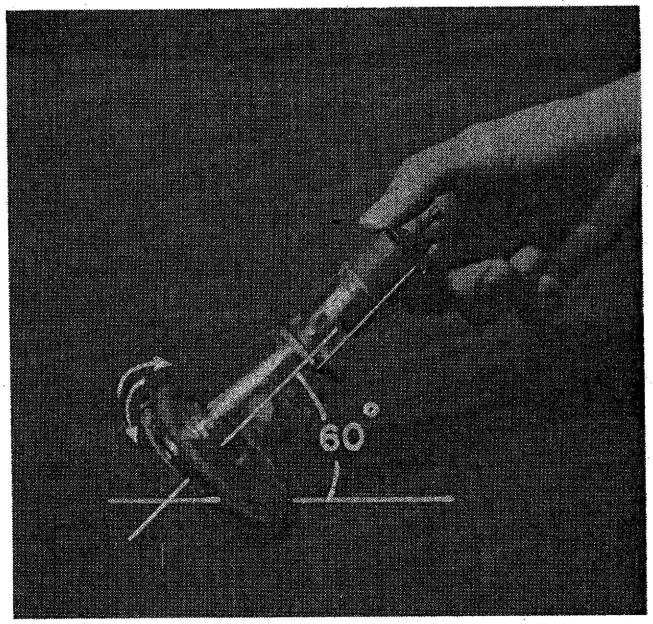
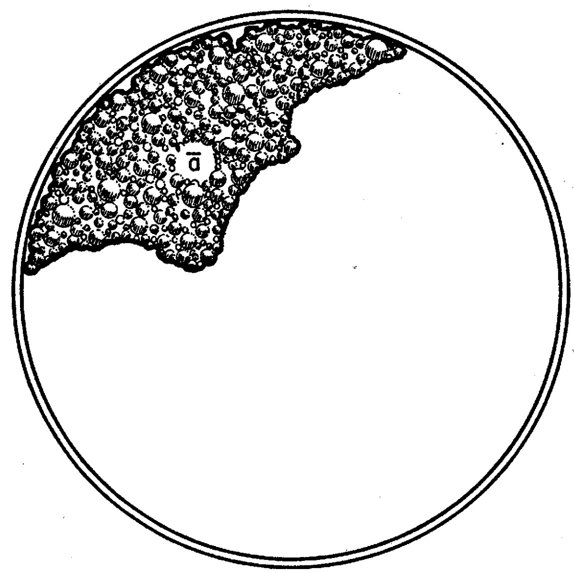


Figure 2-A. Dislodging mortar from brass cup.

5. With the container held at an angle of about 60° to horizontal, rotate as shown in Figure 2-A until the mortar dislodges from the cup. After the mortar is dislodged, gently rotate the container from a vertical to horizontal position several times to disperse the mortar in the distilled water.

6. After the mortar is dispersed in the distilled water, invert the container allowing the air bubbles to rise and collect on the glass plate.



DIAGRAMMATICAL SKETCH SHOWING AREA OF GLASS PLATE COVERED BY BUBBLES

Figure 3-A.

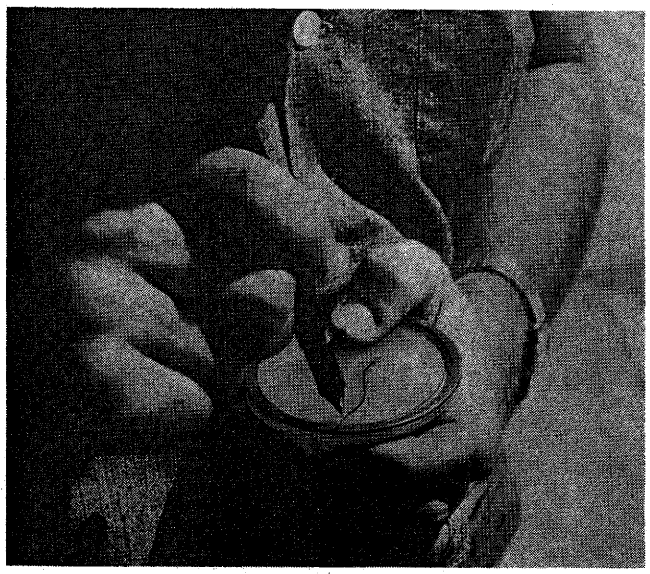


Figure 4-A. Tracing outlined area of bubbles on transparent disc.

7. Tip the container such that the glass plate makes an angle of about 15° to the horizontal. This causes the bubbles to arrange themselves in a closely packed condition as shown diagrammatically in Figure 3-A.

8. With the glass plate in a horizontal position, gently tap the container to arrange the bubbles in one layer against the glass plate.

9. Place the transparent disc shown in Figure 1-A on the glass plate and outline the area covered by bubbles as shown in Figure 4-A. Trace the outlined area with a planimeter to determine $\bar{a}$.

10. Determination of $\bar{V}$ from equation (11) can be simplified by use of Figure 5-A. Locate a horizontal line at the value of $\bar{a}/A$ and a vertical line at the value of P/A. The intersection of these two lines gives the value of $\bar{V}$.

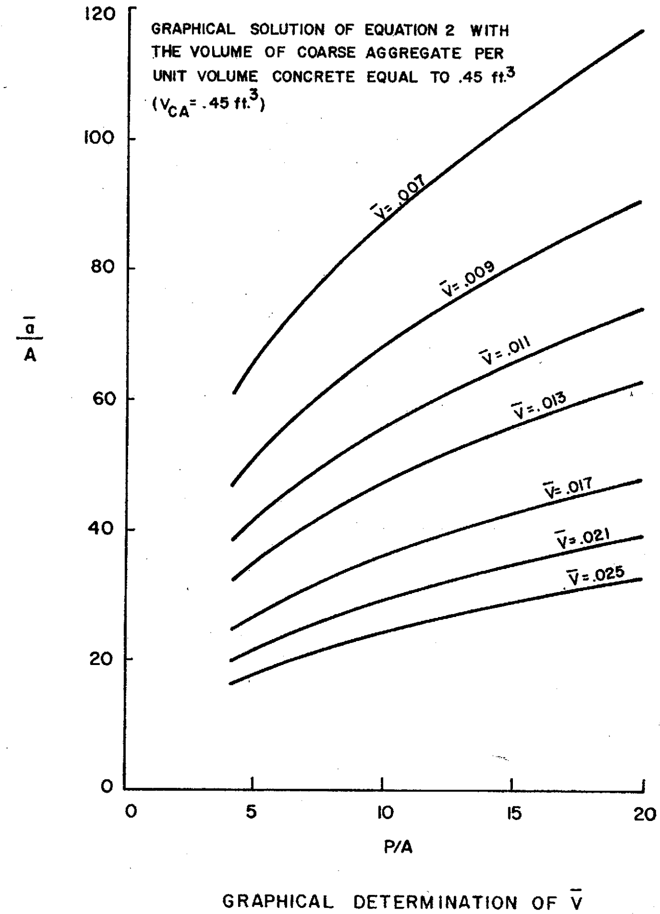


Figure 5-A. Graphical determination of $\bar{V}$.

11. If the value of P/A is not given in Figure 5-A or if the volume of coarse aggregate differs appreciably from .45 ft^3/ft^3 of concrete, then use equation (10) or (11) to determine $\bar{V}$.

Appendix B

TABLE 1-B. PROPERTIES OF FRESH AND HARDENED CONCRETE—FIELD SURVEY PHASE

		Properties of Fresh Concrete			Properties of Hardened Concrete		
Job Designation	Specimen No.	Pressure Meter (%)	VSI (sq. in.)	VSI Spacing Factor (inches)	Volume of Air by ASTM C-457	Powers L (inches)	Durability ASTM C-290 (%)
A	1	5.3	1.77	.0131	3.31	.00690	53.6
	2	5.3	1.77	.0131	2.46	.00687	77.0
	3	5.5	2.24	.0105	3.71	.00688	90.0
B	1	4.4	1.14	.0193	2.98	.01067	33.0
	2	4.4	1.26	.0175	3.14	.00992	57.0
	3	3.5	1.09	.0178	2.86	.01160	16.0
	4	4.6	1.14	.0134	3.14	.01048	29.6
	5	4.3	1.24	.0175	2.89	.01153	34.0
	6	4.2	1.07	.0201	2.57	.01208	18.0
	7	4.7	1.33	.0172	3.17	.01133	23.6
C	1	7.0	1.46	.0146	4.57	.0066	32.6*
	2	4.5	1.78	.0115	4.11	.0084	no specimen cast
	3	7.0	2.64	.0081	5.12	.0064	no specimen cast
	4	4.6	2.60	.0080	4.03	.0068	no specimen cast
	5	3.0	1.81	.0091	2.55	.0085	28.0*
	6	6.2	2.83	.0076	4.61	.0065	49.0*
	7	6.5	2.49	.0086	4.91	.0054	no specimen cast
	8	5.2	1.58	.0137	3.30	.0074	no specimen cast
	9	6.0	1.53	.0141	3.82	.0059	45.4*
	10	5.0	2.03	.0106	3.52	.0084	34.0*
D	1	6.6	1.74	.0126	5.10	.00635	86.2
	2	6.4	1.72	.0127	3.87	.00678	88.2
	3	7.0	2.02	.0108	6.09	.00499	84.0
	4	6.2	2.42	.0091	6.72	.00523	85.0
	5	6.6	2.83	.0077	5.23	.00698	88.0
	6	6.6	2.55	.0086	6.33	.00578	no specimen cast
	7	4.5	1.44	.0141	3.35	.00909	no specimen cast
	8	6.4	3.07	.0071	4.12	.00700	no specimen cast
	9	5.5	2.09	.0110	3.68	.00649	no specimen cast
	10	5.0	1.44	.0149	2.28	.00790	no specimen cast

*Aggregate failures precluded comparison of durability factors with those specimens experiencing paste failures.

TABLE 2-B. PROPERTIES OF FRESH AND HARDENED CONCRETE—READY MIX PHASE

Specimen No.	Properties of Fresh Concrete: Pressure Meter (%)	VSI (sq. in.)	VSI Spacing Factor (inches)	Properties of Hardened Concrete: Volume of Air by ASTM C-457	Powers $\bar{L}$ (inches)	Durability ASTM C-290 (%)
5	5.3	0.960	.0218	3.85	.0160	11.2
8	5.8	1.138	.0190	4.46	.0119	44.0
9	5.4	1.346	.0155	3.01	.0157	59.0
10	5.6	1.299	.0167	4.32	.0163	21.6
11	4.8	1.132	.0175	3.41	.0197	23.6
12	5.7	1.777	.0122	3.80	.0194	63.0
13	5.4	1.339	.0157	4.10	.0172	46.0
14	5.8	1.268	.0172	5.11	.0174	20.4
15	5.4	1.562	.0137	3.32	.0201	33.6
17	5.4	1.323	.0160	3.33	.0153	22.4
18	4.8	1.066	.0185	2.68	.0199	22.0
19	6.1	1.592	.0138	3.33	.0145	38.7
20	4.8	1.224	.0165	3.10	.0163	30.8
21	5.4	1.361	.0158	3.54	.0173	30.9
22	4.8	1.118	.0180	2.84	.0189	32.8
24	4.9	1.171	.0175	2.53	.0205	20.4
27	5.2	1.543	.0146	3.84	.0144	8.8
28	5.3	1.422	.0150	2.93	.0164	32.0
29	5.1	1.477	.0140	2.52	.0184	35.2
33	5.1	1.348	.0155	3.02	.0204	14.8
34	5.2	1.191	.0177	3.01	.0158	11.6
35	5.9	1.548	.0143	2.91	.0137	19.2
36	5.6	1.394	.0158	2.98	.0197	20.4
37	4.6	1.370	.0143	3.08	.0174	28.4
38	5.4	1.320	.0163	3.34	.0159	33.6
39	5.6	1.551	.0142	3.28	.0145	50.2
41	5.2	1.140	.0185	2.37	.0157	23.6
44	6.0	1.843	.0123	3.96	.0102	30.8
45	6.4	1.771	.0123	3.72	.0140	51.8
46	6.0	1.647	.0134	4.05	.0166	24.4
53	5.3	1.338	.0158	3.84	.0170	41.2
54	6.0	1.660	.0132	3.13	.0141	21.0
56	5.9	1.730	.0125	3.45	.0163	86.0
57	6.2	1.860	.0117	3.24	.0187	17.0
58	5.6	1.390	.0157	3.73	.0168	50.4
59	5.8	1.480	.0147	3.22	.0136	13.6

TABLE 3-B. PROPERTIES OF FRESH AND HARDENED CONCRETE—LABORATORY PHASE

	Properties of Fresh Concrete			Properties of Hardened Concrete		
Specimen No.	Pressure Meter (%)	VSI (sq. in.)	VSI Spacing Factor (inches)	Volume of Air by ASTM C-457	Powers $\overline{L}$ (inches)	Durability ASTM C-290 (%)
010	5.6	1.456	.0146	5.24	.00853	94.0
020	5.3	1.172	.0176	5.44	.00989	87.6
030	5.3	1.411	.0146	4.52	.00748	91.3
040	6.0	1.306	.0168	6.64	.00666	89.0
070	5.9	1.634	.0125	6.11	.00586	92.1
080	6.0	1.666	.0127	6.22	.00717	83.8
090	5.7	1.449	.0150	6.66	.00737	87.0
110	5.8	1.367	.0150	6.63	.00551	91.1
120	5.1	1.016	.0203	4.42	.00927	86.5
140	5.1	0.778	.0264	4.53	.0100	81.0
160	5.8	0.999	.0219	4.86	.00830	90.4
170	5.0	1.198	.0168	5.36	.00673	81.2
180	5.2	1.016	.0203	5.03	.00784	92.6
200	6.0	1.030	.0214	5.53	.00727	74.1
210	5.2	0.985	.0214	5.05	.00832	86.0
220	5.3	1.057	.0199	6.17	.00826	92.1
230	6.0	1.654	.0129	5.33	.00516	83.6
240	5.5	1.100	.0188	5.21	.00746	75.2
250	5.1	1.175	.0172	3.91	.00722	77.5
260	5.3	1.069	.0200	4.45	.00935	78.4
270	5.5	1.171	.0173	4.66	.00854	89.2
280	5.4	1.165	.0180	5.12	.00884	86.6
290	5.4	1.008	.0202	4.83	.00803	81.6
300	5.2	1.028	.0203	5.39	.00887	82.0
310	5.5	1.033	.0206	4.57	.00939	85.4
320	5.6	0.850	.0254	5.76	.00959	82.4
330	5.2	1.568	.0132	4.75	.00999	84.4
340	5.7	1.514	.0139	6.21	.00874	77.0
350	5.8	1.310	.0161	5.59	.00974	78.0
360	5.9	1.663	.0124	6.28	.00844	87.0
370	5.8	1.858	.0117	5.57	.00894	77.4
380	6.0	1.02	.0200	6.40	.00725	82.7
390	5.0	1.000	.0203	4.28	.00844	76.0
400	5.7	1.089	.0192	5.14	.00742	81.0
410	5.8	1.408	.0149	6.68	.00803	78.5
420	5.9	1.021	.0207	5.92	.00846	85.0