Correlation Between Concrete Durability And Air-Void Characteristics

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The theory of the action of entrained air in producing frost-resistant concrete demonstrates the importance of the size and distribution of the air voids in the portland cement paste. The characteristics investigated were (a) air content, (b) number of voids intersected per unit length of traverse, (c) specific surface of the air voids, (d) number of hypothetical spheres of equal radius having the same volume of air per unit volume of concrete and the same specific surface as the actual system of random sized voids, and (e) spacing factor.

Statistical methods were applied to the study of the variability of the air content and number of voids per inch within a concrete beam. The analysis showed that the measurement of these characteristics for a particular beam may be considered as one long traverse without regard to the position or length of the individual traverses.

Thirty-eight beams from 19 mixes were used to study the correlation between each of the five air-void characteristics and durability. A durability factor was used to express the resistance of each beam to deterioration in a laboratory freeze-thaw test. The five air-void characteristics ranked in the order of their correlation with durability are (a) spacing factor, (b) specific surface, (c) number of voids per inch, (d) hypothetical number of voids per cubic inch, and (e) total air content.

The spacing factor and the specific surface were found to be of almost equal importance in producing durable concrete. Hence, either of these two characteristics may be used as a criterion for determining the air requirements for frost-resistant concrete.

● THE SUPERIOR performance of air-entrained concrete has been demonstrated in both the field and the laboratory (3, 4, 6, 8, 9, 10, 11). Most reports of research on air entrainment have dealt principally with factors which control the amount of air or with changes in properties of the concrete related to changes in the gross amount of air. However, the current theories of the action of entrained air in producing frost-resistant concrete show that the properties of the air voids themselves are important factors affecting the ability of concrete to withstand freezing and thawing (11, 12, 13, 14).

Considerable research on the effect of air entrainment on the durability of concrete beams as measured by resistance to deterioration under repeated cycles of freezing and thawing has been performed in the laboratories of the Joint Highway Research Project at Purdue University. At times, large differences in durability have been found between beams from the same mix and between mixes made from the same materials and having the same total air content as determined by measurements on the fresh concrete. The study reported in this paper was initiated to determine experimentally which property of the entrained air is most significant in producing durable concrete and to what extent the unexplained differences in durability could be attributed to differences in the characteristics of the void systems of the beams. The air-void characteristics which were investigated for correlation with durability were (a) total air content, (b) number of voids per inch, (c) specific surface, (d) hypothetical number of voids per cubic inch, and (e) spacing factor.

Equipment and procedures similar to those developed in the Portland Cement Asso-

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ciation laboratories and reported by Brown and Pierson (5) were used for measuring the air content and number of voids per inch. The other characteristics were computed from the equations presented along with their development in papers by T. C. Powers (12) and T. F. Willis (16). For ready reference these equations are given in the Appendix. As a preliminary study an investigation was made of the variability within a beam of the air content and number of voids per inch. This preliminary study is presented in the Appendix.

MATERIALS

Concrete beams which were fabricated for use in another investigation conducted in the concrete laboratory of the Joint Highway Research Project were selected for examination in this study. These beams were chosen because of unexplained differences in durability between beams made from the same materials under similar conditions.

All beams used in this study were made with crushed limestone coarse aggregate. Data on the coarse aggregates are presented in Table 1. The six coarse aggregates from the sources in the Kokomo formation have poor durability records. The source from the Liston Creek formation has a good field performance record.

The fine aggregate used in all mixes was obtained from a river terrace deposit of glacial origin. This fine aggregate has been used in the Joint Highway Research Project concrete laboratory for years as a standard material and is considered to be a durable material in laboratory freeze-thaw weathering. The bulk saturated surface dry specific gravity of the fine aggregate was 2.65 and the fineness modulus for the gradation was 3.10. The absorption was 1.65 percent by weight.

Type I portland cement from a single clinker batch was used in all mixes. Darex was used as the air-entraining agent for the mixes made with coarse aggregates A_1, A_2, A_3, and A_4, while neutralized Vinsol resin solution was used for the mixes made with coarse aggregates A_5, A_6, and A_7.

Concrete Mixes

All coarse aggregates were vacuum saturated before being incorporated in concrete. Mixes were designed for a water-cement ratio of 0.46 by weight, a cement

TABLE 1

COARSE AGGREGATES

Aggregate Designation	Aggregate Source Number	Laboratory Sample Number	Description	Geological Origin	Bulk Sp Gr	True Sp Gr[a]	Absorption after Evacuation and Saturation (% by wt)	Degree of Saturation[b] (%)
A_1	9-2S	2033-A	Upper 25 ft Ledges 1, 2, 3, 4	Silurian (Kokomo formation)	2.63	2.86	2.69	90
A_2	9-2S	2033-B	Lower 21 ft Ledges 5, 6, 7	Silurian (Kokomo formation)	2.53	2.86	4.66	98
A_3	9-2S	2033-C	Stockpile sample	Silurian (Kokomo formation)	2.57		3.95	
A_4	9-1S	2034	Ledge sample	Silurian (Kokomo formation)	2.45	2.86	5.85	100
A_5	9-5S	2032-A	Upper 24 ft Ledges 1, 2, 3, 4	Silurian (Kokomo formation)	2.59	2.85	3.19	88
A_6	9-5S	2032-B	Lower 24 ft Ledges 5, 6, 7	Silurian (Kokomo formation)	2.46	2.85	5.65	100
A_7	1-1S	2037	Stockpile sample	Silurian (Liston Creek formation)	2.68	2.85	1.98	90

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[a] True specific gravity values were determined by powdering a sample of the aggregate and then using the procedure for the determination of the specific gravity of soils.

[b] Ratio of the pore space filled with water to the total internal pore space of the aggregate particles.

TABLE 2

AIR-VOID CHARACTERISTICS AND DURABILITY FACTORS—INDIVIDUAL BEAMS

Aggregate	Beam Designation	Durability Factor	Air-Void Characteristics of Hardened Concrete				
			Air Content, A (%)	Voids per Inch, n	Specific Surface, α (sq in./cu in.)	Voids per Unit Vol, N (voids per cu in.)	Spacing Factor, L (in.)
A_1	A21	100	4.5	7.4	660	113,000	0.0075
	A22	99	4.9	9.1	740	178,000	0.0065
	A31	52	3.4	3.8	450	27,000	0.0128
	A32	34	3.2	3.5	440	24,000	0.0134
A_2	B11	90	4.0	7.1	710	127,000	0.0074
	B12	27	3.7	6.4	690	108,000	0.0080
	B21	97	4.8	8.6	720	156,000	0.0068
	B23	58	4.2	7.6	720	141,000	0.0071
	B31	26	3.8	4.3	450	31,000	0.0119
	B32	23	3.2	3.5	440	24,000	0.0134
A_3	C11	96	3.9	6.4	660	97,000	0.0081
	C13	91	4.3	7.2	670	114,000	0.0076
	C31	61	3.5	4.3	490	37,000	0.0114
	C32	87	3.2	4.7	590	57,000	0.0100
A_4	422	62	4.5	7.2	640	104,000	0.0078
	423	85	4.8	8.1	670	130,000	0.0072
	432	60	2.9	3.8	520	37,000	0.0117
	433	100	3.2	5.2	650	78,000	0.0090
	441	19	3.3	3.4	410	20,000	0.0139
	442	38	3.7	3.4	370	16,000	0.0149
A_5	SA11	80	3.7	5.5	600	69,000	0.0092
	SA13	99	4.2	7.1	680	115,000	0.0076
	SA21	94	5.0	9.2	740	176,000	0.0065
	SA23	95	4.6	9.3	810	214,000	0.0061
	SA32	90	4.4	7.0	640	100,000	0.0080
	SA33	92	4.2	7.2	690	120,000	0.0075
A_6	SB11	100	10.3	22.2	860	584,000	0.0040
	SB12	95	9.9	20.5	830	498,000	0.0044
	SB21	88	5.5	11.5	840	285,000	0.0055
	SB22	83	5.5	10.7	780	229,000	0.0059
	SB31	57	3.8	4.9	520	46,000	0.0107
	SB33	38	3.8	5.1	540	52,000	0.0100
	SB41	62	4.4	8.6	780	186,000	0.0065
	SB43	45	4.6	8.3	720	153,000	0.0069
	SB52	97	6.3	12.7	810	293,000	0.0053
	SB53	52	6.2	12.8	820	308,000	0.0052
A_7	711	100	3.7	6.3	680	103,000	0.0080
	712	100	3.7	5.6	600	73,000	0.0090

factor of six bags per cubic yard, and a slump of 3 to 4 in. The maximum size of aggregate was 1 in. The air content of the fresh concrete was measured gravimetrically according to ASTM Method C138-44 (1) except that a 0.1 cu ft measure was used because of the small size of the concrete mixes. The concrete used for making the air content determination was discarded. Three concrete beams, 3 x 4 x 16 in., were made from each mix. Curing was by immersion in water for 13 days following removal of the specimens from molds one day after casting.

MEASUREMENT OF DURABILITY

The relative durability of the beams was determined from their resistance to deterioration when subjected to repeated cycles of freezing and thawing. Automatic equipment was used with the freezing and thawing cycles corresponding to ASTM Method C291-52T (1) rapid freezing in air and thawing in water. Approximately seven cycles per day were obtained.

Periodic determinations of the dynamic modulus of elasticity were made to measure the amount of deterioration. Freezing and thawing were continued until a decrease in dynamic E to 50 percent of the original value occurred or until 200 cycles of freezing and thawing were completed.

The seven coarse aggregates described in Table 1 were represented by 19 mixes. The number of mixes using each coarse aggregate varied. Referring to the aggregate designations in Table 1, A_1 was used in two mixes, A_2 in three mixes, A_3 in two mixes, A_4 in three mixes, A_5 in three mixes, A_6 in five mixes, and A_7 in one mix. For use in studying the air-void characteristics two beams were selected from each mix—the most durable and the least durable. Thus, a total of 38 beams from the 19 mixes was studied.

A durability factor was used to express the durability of each beam selected for measurement of the air-void characteristics. This factor was computed following the procedure suggested by Stanton Walker (15). It may be defined as the area under the curve (dynamic E as a percent of the original E plotted against cycles of freezing and thawing) to the left of the 200th cycle and above the 50 percent dynamic E line expressed as a percentage of the total area to the left of the 200th cycle and above the 50 percent dynamic E line. Table 2 gives the values for the durability factor and the five air-void characteristics for each of the 38 beams.

CORRELATION STUDIES

The durability of a given beam was affected by other variables in addition to the entrained air. In particular, the coarse aggregate could be expected to produce considerable differences in durability among the beams, since six of the coarse aggregates were from sources with poor durability records. For a single concrete mix there is a given number of deleterious particles and a large number of manners in which these particles may be distributed in beams made from the mix. Thus, within a mix, large variations in durability could exist as a result of differences in the distributions of deleterious particles in the beams. Variables such as efficiency of vacuum saturation, skill of labor, and location of beams within the freezer could have an effect on the durability. Hence, the beams examined in this study were regarded as a sample randomly selected from a universe of beams in which variables other than the entrained air exist. To determine the relative importance of the five air-void characteristics in producing durable concrete, the correlation technique was used to study the relationship between durability and each air-void characteristic.

Linear Correlation—Individual Beams

The scatter diagram in which the durability factor is plotted against air content is shown in Figure 1. The scatter diagrams using the other air-void characteristics are presented in Figures 2 through 5.

Although it is possible that some curve other than a straight line would give a higher correlation between durability and a given air-void characteristic, it is believed that for the purpose of this study a straight line fitted by the least-squares method is satisfactory. The results of the computations for slopes, correlation coefficients, and regression lines are summarized in Table 3. The t-value for testing the significance of the correlation coefficient is shown. The formula for t was taken from page 88 of "Statistical Theory in Research" by Anderson and Bancroft (2). The significance of the observed t for n-2 degrees of freedom is indicated in the table as well as the percentage of the variation in durability which is explained by the regression line. The regression lines have been plotted on the scatter diagrams.

Because of the large differences in durability which could be introduced by the

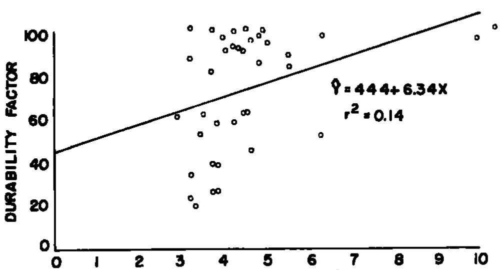

Figure 1. Scatter diagram for durability factor versus air content.

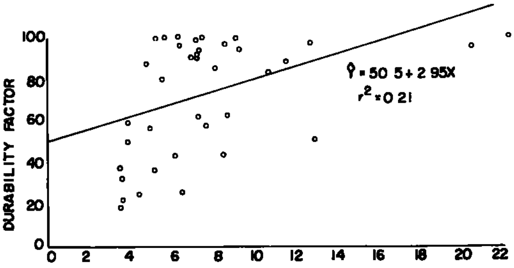

Figure 2. Scatter diagram for durability factor versus number of voids per inch.

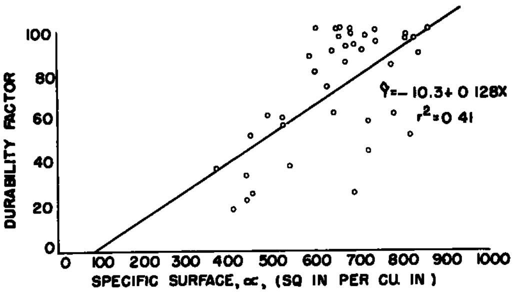

Figure 3. Scatter diagram for durability factor versus specific surface.

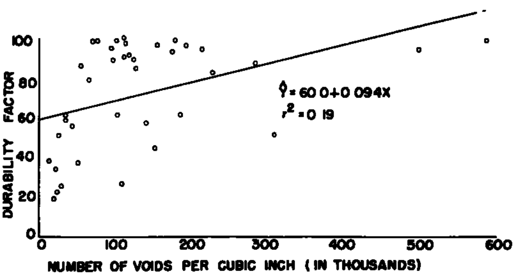

Figure 4. Scatter diagram for durability factor versus number of voids per cubic inch.

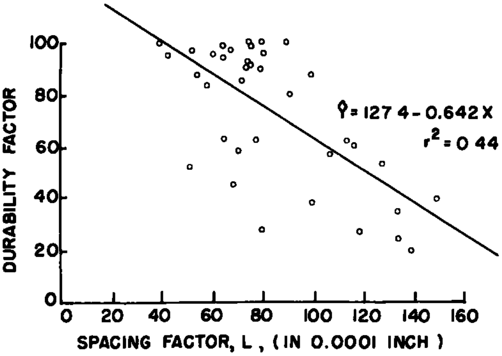

Figure 5. Scatter diagram for durability factor versus spacing factor.

coarse aggregate and other variables these regression lines should not be used to predict the durability factor for a given value of an air-void characteristic. They should be regarded as indicating the trend in the change in durability factor with changes in an air-void characteristic.

Linear Correlation—Average Values for Each Mix

In order to study correlation between durability and air-void characteristics on a mix basis an analysis was made using the average values for each mix. Since freeze-thaw data were available on three beams from each mix, the durability factor for each mix was taken as the average for the three beams. Average values for the durability factor and five air-void characteristics for each mix are given in Table 4. The value for each air-void characteristic is the average for the two beams from the values given in Table 2. The results of this correlation study are summarized in Table 5.

Discussion of Correlation Studies

The graphs of the durability factor plotted against each of the five air-void characteristics (Figs. 1-5) show considerable scatter. Some of this scatter would be expected to result from the coarse-aggregate variable. Inspection of the scatter diagrams alone would lead one to conclude that little correlation exists between the total air content and durability for the beams examined. In the past the total air content has been the air-void characteristic most used in determining the air requirements for frost-resistant concrete.

The air-void characteristics (specific surface and spacing factor) which are computed from equations containing both air content and number of voids per inch show the smallest amount of scatter. This indicates the importance of the interaction of these two characteristics in producing durable concrete. Inspection of Tables 3 and 5 also shows the importance of the interaction of air content and number of voids per inch in producing durable concrete. The specific surface and spacing factor give considerably higher correlation coefficients than the other three characteristics.

Tables 3 and 5 show that the correlation coefficient obtained using the average values for each mix is noticeably higher for each air-void characteristic than the corresponding value computed from the data for individual beams. This results from eliminating the large differences in durability between beams within the same mix by means of averaging the individual values. A large part of this difference in durability within a mix can be attributed to the coarse aggregate, since differences in the combinations

TABLE 3

SUMMARY OF STUDY OF LINEAR CORRELATION BETWEEN DURABILITY AND AIR-VOID CHARACTERISTICS INDIVIDUAL BEAMS

Air-Void Characteristic	$\bar{Y}$	$\bar{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{obs.} = r\sqrt{\frac{n-2}{1-r^2}}$	Significance	Variation Explained by Regression Line (%)
Air content, A (%)	72.9	4.49	6.338	Y = 44.4 + 6.34X	0.3698	2.39	a	13.67
Number of voids per inch, n	72.9	7.62	2.946	Y = 50.5 + 2.95X	0.4542	3.06	c	20.63
Specific surface, α (sq in./cu in.)	72.9	648.2	0.1284	Y = -10.3 + 0.128X	0.6370	4.96	c	40.58
Voids per unit volume, N (thousands of voids per cu in.)	72.9	137.4	0.0941	Y = 60.0 + 0.094X	0.4349	2.90	b	18.92
Spacing factor, L (0.0001 in.)	72.9	84.9	-0.6416	Y = 127.4 - 0.642X	-0.6647	5.34	c	44.18

Note: Y = Durability factor X = Air-void characteristic

$t_{0.9875} = 2.34$ $t_{0.995} = 2.72$ $t_{0.9975} = 2.99$

[a] $t_{obs.} > 2.34$ [b] $t_{obs.} > 2.72$ [c] $t_{obs.} > 2.99$

TABLE 4

AVERAGE AIR-VOID CHARACTERISTICS AND DURABILITY FACTORS FOR EACH LABORATORY MIX

				Air-Void Characteristics of Hardened Concrete				
Aggregate	Mix Designation	Durability Factor	Air Content as Measured on Fresh Concrete	Air Content, A (%)	Voids per Inch, n	Specific Surface, α (sq in./cu in.)	Voids per Unit Volume, N (voids/cu in.)	Spacing Factor, L (in.)
A_1	33-A2	99	4.3	4.7	8.3	700	146,000	0.0070
	33-A3	40	3.8	3.3	3.7	450	26,000	0.0131
A_2	33-B1	70	3.6	3.9	6.8	700	118,000	0.0077
	33-B2	84	4.7	4.5	8.1	720	149,000	0.0070
	33-B3	23	3.0	3.5	3.9	450	28,000	0.0127
A_3	33-C1	94	4.4	4.1	6.8	670	106,000	0.0079
	33-C3	78	3.8	3.4	4.5	540	47,000	0.0107
A_4	34-2	74	4.4	4.7	7.7	660	117,000	0.0075
	34-3	70	3.5	3.1	4.5	590	58,000	0.0104
	34-4	30	3.3	3.5	3.4	390	18,000	0.0144
A_5	SA-1	90	3.4	4.0	6.3	640	92,000	0.0084
	SA-2	94	4.7	4.8	9.3	780	195,000	0.0063
	SA-3	91	3.7	4.3	7.1	670	110,000	0.0078
A_6	SB-1	96	9.9	10.1	21.4	850	541,000	0.0042
	SB-2	85	6.2	5.5	11.1	810	257,000	0.0057
	SB-3	51	3.9	3.8	5.0	530	49,000	0.0104
	SB-4	57	4.9	4.5	8.5	750	170,000	0.0067
	SB-5	82	7.5	6.3	12.8	820	302,000	0.0053
A_7	37-1	100	3.9	3.7	6.0	640	88,000	0.0085

TABLE 5

SUMMARY OF STUDY OF LINEAR CORRELATION BETWEEN DURABILITY AND AIR-VOID CHARACTERISTICS AVERAGE VALUES FOR EACH MIX

Air-Void Characteristic	$\bar{Y}$	$\bar{X}$	Slope (b)	Regression Line Y on X	Correlation Coefficient (r)	$t_{obs.} = r\sqrt{\frac{n-2}{1-r^2}}$	Significance	Variation Explained by Regression Line (%)
Air content, A (%)	74.1	4.51	6.202	Y = 46.1 + 6.20X	0.4134	1.87	a	17.09
Number of voids per inch, n	74.1	7.64	2.903	Y = 51.9 + 2.90X	0.5138	2.47	c	26.40
Specific surface, α (sq in./cu in.)	74.1	650.5	0.1338	Y = -12.9 + 0.134X	0.7560	4.62	e	55.66
Voids per unit volume, N (thousands of voids per cu in.)	74.1	137.7	0.0940	Y = 61.2 + 0.094X	0.4952	2.35	b	24.53
Spacing factor, L (0.0001 in.)	74.1	85.1	0.6641	Y = 130.6 - 0.664X	0.7792	5.13	e	60.72

Note: Y = Durability factor X = Air-void characteristic

$t_{0.95} = 1.74$ $t_{0.975} = 2.11$ $t_{0.9875} = 2.46$ $t_{0.995} = 2.90$ $t_{0.9975} = 3.22$

[a] $t_{obs.} > 1.74$ [b] $t_{obs.} > 2.11$ [c] $t_{obs} > 2.46$ [d] $t_{obs.} > 2.90$ [e] $t_{obs} > 3.22$

of deleterious particles in the beams result in variations in durability.

Table 3 shows that 44 percent of the variation in durability can be attributed to differences in spacing factor based on the data for individual beams while Table 5 shows a corresponding value of 61 percent using average values for each mix. In Figure 6 durability factor is plotted against spacing factor using the mix values. Comparison with Figure 5 shows considerable reduction in scatter when mix values are used.

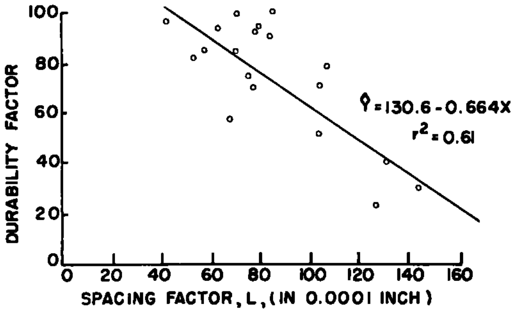

Figure 6. Scatter diagram for durability factor versus spacing factor, average values for mixes.

Although there may be a better way to express the size and distribution of the air voids in portland cement paste than the spacing factor used in this study, the results of the correlation studies emphasize the importance of size and distribution in producing frost-resistant concrete.

SUMMARY OF RESULTS

The results of the work completed in this investigation may be summarized as follows:

1. The current theoretical explanations of the action of entrained air in producing frost-resistant concrete show the importance of the size and distribution of the air voids. The correlation studies of the relationship between each of the air-void characteristics and durability show the spacing factor to be most highly correlated with durability factor. Using the data on individual beams, 44 percent of the differences in durability can be explained by the differences in the spacing factor. Using average values for each mix, 61 percent of the differences in durability can be explained by differences in the spacing factor. Thus, the results of this investigation are in agreement with the current theories.
2. The specific surface is almost as highly correlated with durability as the spacing factor with 41 percent of the variation in durability being explained by the differences in the specific surface when the data on the individual beams are used. Using average values for each mix 56 percent of the variation in durability can be explained by differences in the specific surface.
3. The five air-void characteristics ranked in the order of their correlation with durability beginning with the one showing the best correlation are (a) spacing factor, (b) specific surface, (c) number of voids per inch, (d) hypothetical number of voids per cubic inch, and (e) total air content.
4. Since the specific surface is almost as highly correlated with durability factor as the void spacing factor, either of these two characteristics is probably a satisfactory guide for determining the air requirements for frost-resistant concrete. The correlation between each of these two characteristics and durability was found to be significant at the 99.75 percent confidence level.

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Appendix

FORMULAS FOR COMPUTATION OF AIR-VOID CHARACTERISTICS

The air-void characteristics which were investigated for correlation with durability were:

A = air content, total volume of voids per unit volume of concrete, percent,
n = number of voids intersected per unit length of traverse, voids per inch,
α = the specific surface of the air voids, the surface area of the voids per unit volume of air, square inches per cubic inch,
N = number of hypothetical spheres all having the same radius r_h that would give a

volume of air equal to the actual air content of the concrete, voids per cubic inch, and

L = spacing factor, distance from void boundary to outer boundary of sphere of influence, inches.

Two of the characteristics, A and n, were measured directly with the linear traverse integrator shown in Figure 7. The remaining three were computed from these two measurements with the paste content being introduced in the computation of the spacing factor.

The equations that were used for the computation of α, N, and L were presented along with their development in the paper "The Air Requirement of Frost-Resistant Concrete" by T.C. Powers (12) and a discussion of the same paper by T. F. Willis (16).

T. F. Willis (16) showed that regardless of the size distribution of the voids the true specific surface of the voids is given by the equation:

$$\alpha = \frac{4n}{A} \qquad \text{(Eq. 1)}$$

N and L are obtained by assuming that the voids are equal size spheres with the size determined by the specific surface. Powers (12) and Willis (16) show that the radius r_h of this hypothetical sphere is equal to $\frac{3}{\alpha}$. This hypothetical number of spheres, N, may be computed from the following formula:

$$N = \frac{A\,\alpha^3}{36\,\pi} \qquad \text{(Eq. 2)}$$

To compute the spacing factor for the hypothetical void system, each sphere is considered to be at the center of a cube with the sum of the volumes of all such cubes and the enclosed spheres equaling the combined air and paste content of the concrete. The "sphere of influence" of each void is the radius of the sphere circumscribing the hypothetical cube. The spheres will overlap except at the corners of the cubes. The radius of the sphere of influence is equal to one-half the diagonal of the cube.

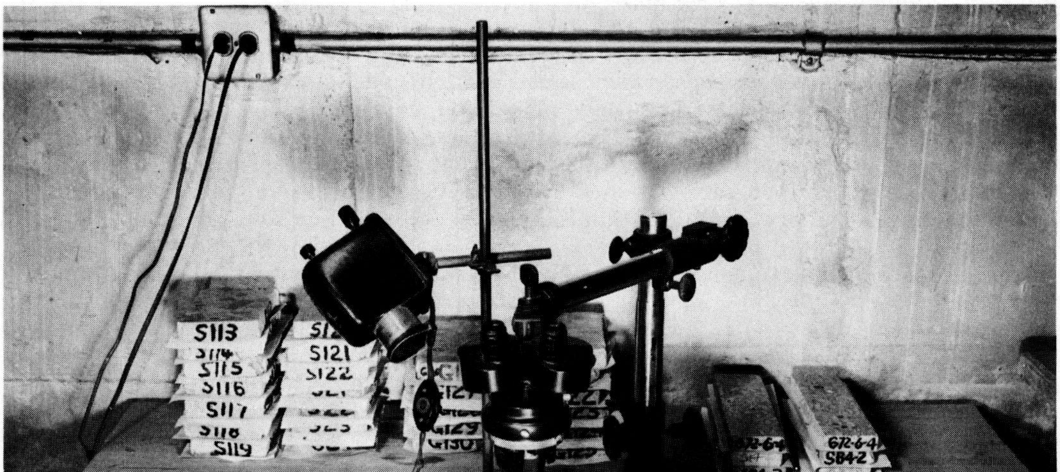

Figure 7. Linear Traverse Integrator.

The volume of the single hypothetical cube is $\frac{p + A}{N}$ where p = paste content (sum of volumes of water and cement per unit volume of concrete). Hence, the length of one edge of the hypothetical cube is $\left(\frac{p + A}{N}\right)^{1/3}$.

And,

$$r_m = \frac{\sqrt{3}}{2} \left(\frac{p + A}{N}\right)^{1/3} \qquad \text{(Eq. 3)}$$

where r_m = radius of circumscribed sphere, the "sphere of influence."

The spacing factor L is equal to the difference between the radius of the sphere of influence r_m and the radius of the sphere r_h: that is,

$$L = r_m - r_h \qquad \text{(Eq. 4)}$$

STUDY OF POSITION AND LENGTH OF TRAVERSE

The Rosiwal method of determining the percentage by volume of the constituents of a solid requires that a random line be passed through the solid. This principle is applied to a sample of concrete by first exposing a random section and then running a random traverse line in the plane of the section. In the actual application to a given beam the four surfaces of the beam are considered to have been randomly selected with respect to the concrete mix from which the beam was made.

In order to determine the effect, if any, of the position of the traverse within the beam an investigation of the variability of the air content and number of voids per inch within the beam was made. Also, the effect of the length of traverse on the reliability of the measurements was studied. For this investigation two beams from a concrete mix containing a durable coarse aggregate were selected for examination. Each of these beams had withstood 800 cycles of freezing and thawing without any loss in dynamic modulus of elasticity.

The original beam dimensions were 3 x 4 x 16 in. Three inches were removed from each end of the beams by sawing. Then three cuts were made longitudinally through the 3-in. dimension so that four slabs approximately ¾-in. thick were produced from each beam. Three surfaces from each beam were polished for examination by the linear traverse integrator. The three surfaces selected for examination were those which could be considered to represent three vertical planes spaced through the beam at approximately 1-in. intervals. These planes are designated 1', 2', and 3' in Figure 8.

To study the effect of using traverses of different lengths, determinations of the air content were made using traverses of four different lengths. Four equally spaced traverses were measured on each polished surface. Thus the twelve traverses in each beam could be considered to fall within either three vertical or four horizontal planes as shown in Figure 8.

An estimate of the air content of each beam was made using the first 4 in. of each traverse starting at the right edge and moving the beam to the right. Estimates were then made using the first 6 in. of each traverse. Then the first 8 in. of each traverse were used. Finally all 10 in. of each traverse were examined. The estimates for each traverse are given in Table 6.

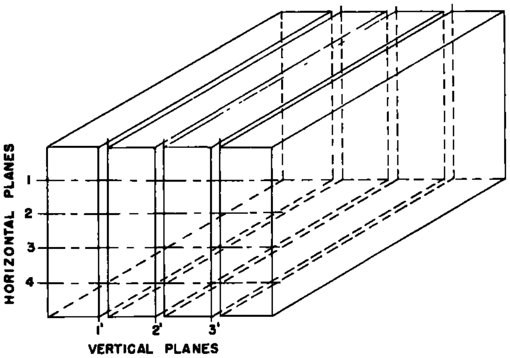

Figure 8. Position of traverses with respect to horizontal and vertical planes in beam.

Statistical Analysis

The statistical procedure known as the "analysis of variance" (8) for testing for significant differences among two or more means was followed to determine if the measured air content is influenced by the position of the traverses with respect to horizontal or vertical planes within the beam. The results of this method of analysis are usually presented in an analysis-of-variance table such as Table 7. The F ratio is used to test for significance. It is formed in this case by taking the mean square found on the line whose effect is being tested and dividing by the mean square of the next lower subgroup in the sampling procedure. If this ratio is less than the F ratio at some chosen level of significance based on the Fisher variance ratio probability law, then it may be concluded that the particular factor being tested is not significant. The F ratios for a significance level of 5 percent are $F_{0.95}$ (6, 16) = 2.74 for horizontal planes and $F_{0.95}$ (4, 18) = 2.93 for vertical planes. Table 7 shows an F ratio of 0.83 for horizontal planes and an F ratio of 1.67 for vertical planes. Similar results were obtained in the study of the variability of the number of voids per inch. Hence, it may be concluded that air content and number of voids per inch may be determined without regard to the horizontal or vertical planes within which the traverses may fall.

A 90 percent confidence level for determining the air content of an individual beam within ± 0.5 percent of the true air content was selected. Table 8 presents the results of the study of the effect of the length of the individual traverse on the confidence limits for the mean air content. The standard error of the mean is shown to decrease as the length of the traverse is increased with the total number of traverses remaining the same. When the standard error of the mean is computed on the basis of a total of 120 in. of traverses, it is approximately 0.3 for traverses of all lengths. Very similar results were obtained for the number of voids per inch. Therefore, the total length of the traverses determines the confidence limits for the air content and number of voids per inch rather than the length of an individual traverse.

The individual traverses examined in the measurement of the air content and number of voids per inch of a beam may be considered as one long traverse. Table 8 shows that the length of this traverse should be approximately 135 in. to give the air content of a beam of the type studied within ± 0.5 percent of the true air content. In order to allow for some increase in variability when examining concrete from other mixes, 100 in. of traverses on each of two surfaces (200 in. total) were selected as

TABLE 6

AIR CONTENT ESTIMATES (PERCENT)—INDIVIDUAL TRAVERSES OF DIFFERENT LENGTHS

Length of Traverses (in.)	Horizontal Planes	Beam I Vertical Planes			Beam II Vertical Planes		
		1'	2'	3'	1'	2'	3'
Four	1	3.47	2.68	7.50	6.17	4.03	3.22
	2	0.99	2.50	3.23	2.98	0.74	5.00
	3	0.75	2.99	3.46	3.70	1.27	1.76
	4	2.98	2.99	2.50	5.94	2.75	2.75
Six	1	3.17	2.32	6.25	5.47	4.13	3.65
	2	1.83	4.29	2.64	2.48	0.83	3.81
	3	1.17	3.17	3.82	3.50	2.15	2.32
	4	4.13	3.01	2.00	4.29	3.17	3.65
Eight	1	3.99	2.59	5.59	4.76	3.75	4.23
	2	2.25	3.94	3.26	2.74	2.99	5.90
	3	1.62	2.74	3.39	3.27	2.13	2.13
	4	4.35	2.62	3.91	5.47	3.75	3.75
Ten	1	4.10	2.63	6.64	4.38	3.71	3.66
	2	2.20	3.47	3.45	2.80	3.00	5.47
	3	3.00	2.66	3.29	2.98	1.85	3.90
	4	5.19	2.51	3.86	4.73	3.29	3.68

TABLE 7

ANALYSIS OF VARIANCE—AIR CONTENT (PERCENT)

Planes	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Horizontal	Beams	0.0084	1	0.0084	0.01
	Pl. in Bm.	6.5401	6	1.0900	0.83
	Tr. in Pl.	21.0441	16	1.3153	
	Total	27.5926	23		
Vertical	Beams	0.0084	1	0.0084	0.00
	Pl. in Bm.	7.4788	4	1.8697	1.67
	Tr. in Pl.	20.1054	18	1.1170	
	Total	27.5926	23		

$F_{0.95}$ (4, 18) = 2.93 $F_{0.95}$ (6, 16) = 2.74

TABLE 8

CONFIDENCE LIMITS FOR AIR CONTENT (PERCENT)—TRAVERSES OF DIFFERENT LENGTHS

Length of Traverses (in.)	Error Mean Square	Std Error of Mean $S_{\bar{x}}$	Confidence Limits for Beam (90% confidence level)		$S_{\bar{x}}$ for 120 Inches of Traverses	Total Length of Traverses Required for 90 Percent Confidence Intervals To Be 1 Percent Long (in.)
			Beam I	Beam II		
Four	2.861	0.488	3.00 ± 0.83	3.36 ± 0.83	0.309	136
Six	1.649	0.371	3.15 ± 0.63	3.29 ± 0.63	0.287	120
Eight	1.304	0.330	3.35 ± 0.56	3.74 ± 0.56	0.295	124
Ten	1.254	0.323	3.58 ± 0.55	3.62 ± 0.55	0.323	150
					Average 0.303	Average 133

standard procedure for the measurements. Thus the results of the study of the position and length of the traverse substantiate the procedure followed by other investigators (5) for the measurement of air in hardened concrete.