Determination of Properties of Air Voids in Concrete

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A METHOD was developed which makes it possible to determine the characteristics of the entrained air voids in concrete. Briefly, the procedure consisted of cutting and polishing a section of concrete to expose the distributed voids. The voids thus exposed were then filled with a fluorescent material and photographed under ultraviolet light. After determining the size distribution and number of voids appearing on a photograph, equations derived by using the methods of mathematical statistics were applied to determine the true properties of the distributed voids.

Application of the method made it possible to compare the void properties in different types of concrete containing various percentages of entrained air. The effects of the two most widely used air-entraining agents, Darex and Vinsol resin, were also compared.

Information obtained from the tests indicates that the average diameter of the voids in concrete may vary from about 0.1 mm. in normal concrete to less than half that size in air-entrained concrete. The number of voids per unit volume of concrete increased greatly with a small addition of entrained air; and for a given amount of entrained air, concrete with a high cement content contained more voids per unit volume than concrete with a low cement content. Darex and Vinsol resin produced entrained voids which had almost identical characteristics.

● SMALL air voids distributed throughout the paste component of concrete greatly increase the ability of concrete to withstand freezing and thawing conditions. For several years this fact has been common knowledge to the majority of concrete technologists, and numerous studies have been conducted to ascertain the effect of entrained air on the properties of concrete. However, while most previous studies have been confined to the measurement of the total volume of entrained air, theoretical and practical considerations suggest that the properties of the air voids may be an important factor influencing the ability of concrete to withstand freezing and thawing conditions.

Using the hydraulic-pressure hypothesis, Powers (1) derived equations to show how durability is influenced by various properties of the voids in air-entrained concrete. However, as suggested by Powers, it is felt that the derivation of such equations is not sufficiently rigorous to warrant their use by direct application. An effort was made in this investigation to develop a satisfactory method for determining the actual character of entrained voids in concrete so that more-exacting empirical studies may be made to determine the air requirement of durable concrete.

PLANE-INTERCEPT METHOD FOR ANALYZING THE VOIDS IN CONCRETE

Results Desired

Preliminary study of the problem of void analysis served to point out that it would be desirable to know the following properties of the voids in concrete: (1) average void diameter, (2) specific surface of the voids, (3) number of voids per unit volume of concrete, (4) total volume of voids per unit volume of concrete, and (5) void spacing factor.

The primary purpose for wanting to determine the average void diameter and the number of voids per unit volume of

concrete was to establish the necessary parameters for determining the void spacing factor. It is believed that the void spacing factor, i.e., half the average maximum distance from surface of void to surface of void within the paste component of the concrete, is perhaps the most-important void property influencing concrete durability.

It was desired to determine the specific surface of the voids to give an indication of the size of the voids in concretes with different air contents. Specific surface is defined herein as the surface area of the voids per unit volume of air in the concrete. As such, it is not directly dependent upon the number of voids per unit volume of concrete.

The total volume of voids per unit volume of concrete was measured as an independent check on the air content as measured on the fresh concrete.

The basic approach, using the plane-intercept method, was to pass a plane through the concrete and measure the diameters of the circles transcribed when the plane intercepted voids and then, by a mathematical analysis of the data obtained, determine the properties of the entrained voids.

Mathematical Relationships

Before the plane-intercept method could be applied, it was first necessary to derive equations relating the void properties as measured on a plane passing through the voids to the actual properties of the voids.

If, in a distribution of scalar quantities, there is a number a_1 of m_1 magnitude, a_2 of m_2 magnitude, a_3 of m_3 magnitude, etc., the arithmetic mean of the magnitudes is defined as

$$[m]_1 = \frac{a_1m_1 + a_2m_2 + a_3m_3 + \cdots a_im_i}{a_1 + a_2 + a_3 + \cdots a_i} = \frac{\Sigma(am)}{\Sigma a}.$$

This quantity, in mathematical statistics, would also be referred to as the first moment of the series of magnitudes m_1, m_2, m_3, etc. Using the same general notation, it is also possible to define other moments of a series of magnitudes that can be shown to have significance. Thus, the nth moment of a series of magnitudes can be written as

$$[m]_n = \frac{\Sigma(am^n)}{\Sigma a}.$$

When a plane is passed through a section of concrete containing a dispersion of spherical voids, the diameters of the circles transcribed on the plane may be placed into particular size classes. Each circle falling within a particular size class may be considered as having a size equal to the average size of the size class. If this is done, then it is possible to treat the distribution of circle sizes statistically, and by definition, the first moment of the transcribed circle diameters will be

$$[l]_1 = \frac{a_1l_1 + a_2l_2 + a_3l_3 + \cdots a_il_i}{a_1 + a_2 + a_3 + \cdots a_i},$$

where a_1, a_2, a_3, etc., are the number of transcribed circles having diameters l_1, l_2, l_3, etc., respectively. By applying the definition for other moments of l, the nth moment is

$$[l]_n = \frac{\Sigma(al^n)}{\Sigma a}.$$

It is important to note that n need not be a positive integer; specifically, in two of the equations below it is necessary to use the -1 moment of l.

The equations relating the true void properties listed above to the properties of the circles transcribed on an interception plane were found to be as follows:[1]

1. The average diameter of the spheres in the distribution of sphere sizes is

$$D_a = \frac{\pi}{2[l]_{-1}}. \tag{1}$$

2. The specific surface of the distributed spheres is

$$\sigma = \frac{16}{\pi}\frac{[l]_1}{[l]_2}. \tag{2}$$

3. The number of spheres per unit volume of concrete is

[1]After deriving the equations presented herein, the writer obtained a paper by Willis (2) in which there is also a solution of the problem. The equations derived by the writer check those derived by Willis. In addition, the writer also derived a mathematical relationship giving the actual size distribution of the voids as a function of the size distribution of the circles transcribed on an interception plane. This relationship is not presented or discussed herein, since it is not pertinent to the results given.

$$M = \frac{2n\,[l]^{-1}}{\pi}, \tag{3}$$

where n is the number of voids intercepted per unit area of the intercepting plane.

4. The air content per unit volume of concrete is

$$V_t = \frac{\pi\, n\,[l]^2}{4}. \tag{4}$$

5. The void spacing factor[3] is

$$= \frac{\sqrt{3}}{2}\left(\frac{p + V_t}{M}\right)^{1/3} - \frac{D_a}{2}, \tag{5}$$

where p is the paste content of the concrete (sum of the volumes of cement and water).

Obtaining a Picture of Air Voids

By observing several cut and polished surfaces of air-entrained concrete under high magnification, it was concluded that air-entrained voids vary considerably in size and that the smallest existing voids are usually on the order of a few ten thousandths of an inch in diameter. It was further concluded that perhaps the easiest way to analyze the voids as they appear on an interception plane would be to measure them with a scale on an enlarged image.

If a microphotograph of air-entrained concrete is taken using ordinary light, it is difficult to distinguish the air voids, even if the light rays strike the concrete at an oblique angle. Thus, the conclusion was drawn that it would be very desirable to obtain an enlarged photograph of the voids only. This was accomplished by filling the voids with a fluorescent dye and photographing them under ultraviolet light. The main problem encountered in using this method is to develop a procedure for successfully filling with a fluorescent material all of the voids that appeared on a cut section of the concrete. As a preliminary to solving the problem, a survey was made of most of the well-known fluorescent materials. The result was a decision to use some vehicle for introducing a fluorescent dye into the voids.

[3] This equation is analogous to the equation derived by Powers (1) for the same quantity

Canada balsam, a turpentine yielded by the balsam fir, is a transparent, viscous liquid when received, but it solidifies if certain volatile constituents are allowed to evaporate. By careful heating, enough of the volatile constituents can be driven out so that it will be quite hard at room temperature but liquid at higher temperatures; thus, by proper manipulation, its viscosity can be varied at will, within limits. Considering these physical properties, it was concluded that Canada balsam would be an almost ideal medium to use in getting a fluorescent dye into the voids of hardened concrete. One difficulty lay in finding a fluorescent dye that would be soluble in this medium. After trying several fluorescent materials, it was found that a dye produced by the Magnaflux Corporation and marketed as dye No. 5GA was quite satisfactory.

Some difficulty is encountered in cutting and grinding a surface of concrete without some harm to the void structure. It is particularly difficult to prevent breakdown of the edges of a void if it is intercepted by the cut plane so that most of the void volume still lies within the concrete. For this reason, an attempt was made to impregnate completely small sections of concrete from 0.1 to 0.5 in. in thickness. Several impregnation schemes were tried, the most successful one being a vacuum-pressure method described by Waldo and Yuster (3). While it was possible to obtain almost complete impregnation of the capillary pores in the concrete, the larger internal voids became only partially filled. The idea of complete impregnation with Canada balsam was, therefore, abandoned. The method that was adopted for filling the voids with Canada balsam containing fluorescent dye is described below.

Choosing a suitable ultraviolet light source was not a difficult problem. One requirement was that the ultraviolet source emit most of its energy between 3,000 and 4,000 Angstroms, since wave lengths below 3,000 Angstroms are considered harmful to the human eye. The type lamp selected was a 100-watt mercury-vapor lamp with a red-purple filter as an outer bulb. It is designated by the manufacturer, the General Electric Company, as a Type B-4H bulb.

The fluorescent material used emitted

light of greenish-yellow color - about in the range 5,200 to 5,600 Angstroms, which includes the peak of eye sensitivity. In photographing the voids, the basic idea was to select a film that would be insensitive to anything above 5,600 Angstroms, with its maximum sensitivity at more than 5,200 Angstroms; then to select a filter that would screen out nearly all light in the blue, violet, and ultraviolet range. By inspecting the sensitivity curves for various films and the spectral transmission curves for various filters, Kodak Contrast Process Ortho film and a Wratten G- No. 15 filter was selected. This combination proved to be satisfactory.

The complete process for obtaining an enlarged image of the voids in a particular piece of concrete was as follows:

1. A section of concrete approximately ½ in. thick was cut from the concrete using a diamond saw. The size of the section was of no particular significance, except that it was large enough so it could be handled conveniently.

2. The cut section was ground on a wet cast-iron lap using coarse silicon carbide-Carborundum No. 120GG. This grinding was continued until all saw marks were removed. The concrete was then washed thoroughly with water and brushed with a small brush to remove the coarse abrasive.

3. Further grinding was then done on a wet cast-iron lap using medium silicon carbide-Carborundum No. FFF.

4. Final wet grinding was done on plate glass; first using Carborundum No. FFF and then a fine emery, American Optical Company, Emery No. 303. The reason for using the carborundum for grinding on plate glass was to insure a plane surface on the concrete. The emery was used to give a smooth surface to the area between voids. After the final grinding operation, the ground surface was again washed with water and the abrasive was blown out of the voids with low-pressure compressed air. The concrete surface was then suitably prepared so the intercepted voids could be filled with the fluorescent material.

5. To prepare the Canada balsam as a suitable medium for holding the fluorescent dye, it was maintained at 130 C. for 20 to 30 min. to drive off enough volatile material to make it hard at room temperature. While still at 130 C., approximately 2 percent, by weight, of fluorescent dye No. 5GA was added. The Canada balsam was stirred until the dye dissolved and was then allowed to cool.

6. The ground concrete section was heated for an hour in an oven at 80 C. and simultaneously the fluorescent material was heated to a temperature of 90 C. The section was then taken out of the oven and the liquid fluorescent material was quickly spread over the prepared surface with a spatula.

7. Before the concrete had time to cool appreciably, it was placed in an air-tight vessel and a vacuum of about 2 psi. absolute pressure was quickly drawn with a small vacuum pump. This served to draw the air out of the voids on the surface and insure their being filled with the fluorescent material. After the vacuum was released, the excess fluorescent material was removed with a spatula and the concrete was allowed to cool.

8. After cooling, the concrete surface had a slight excess of fluorescent material on it, more than just enough to fill the voids. The excess was ground off on a piece of wet plate glass in two steps, first using Carborundum No. FFF and then using Emery No. 303. This final operation was somewhat tedious, since too much grinding exposed voids not originally filled with fluorescent material and insufficient grinding caused the spaces between voids to show up under the ultraviolet light. By observation under ordinary light it was possible to tell when most of the fluorescent coating was ground off. The final grinding operation was done by alternately grinding and observing the appearance of the concrete under the ultraviolet light. Using this procedure, it was easy to tell when all of the excess fluorescent material had been removed. The voids in the concrete were now completely filled with the fluorescent material and were ready to be photographed.

9. Photographing was done on 5- by 7-in. Kodak Contrast Process Ortho sheet film. The prepared concrete section was placed under the camera lens and the ultraviolet light source was placed as close to the concrete as practicable. A Wratten G- No. 15 filter was placed between the

camera lens and the film. Initial magnification, i. e., the ratio of size of image on the film to size of object on the concrete, was six diameters. This magnification required an exposure time of 8 min. at a lens setting of f:9.8. The film was developed for 9 min. in Kodak D-11 developer.

10. After the film was developed, two small areas on the negative were masked off using black scotch tape. These areas were enlarged to 7- by 9-in. size and printed on Kodabromide F3 paper. The size of the areas masked off determined the final amount of magnification. As a general rule, non-air-entrained concrete was magnified 20 diameters, and air-entrained concrete was magnified 40 diameters. A print of a 5- by 7-in. negative with two areas masked off is shown in Figure 1, while Figure 2 shows an enlarged print of one of the masked areas. These figures were obtained from a section of concrete with a cement factor of 7 sacks per cu. yd. and a net air content of 6.7 percent as determined on the fresh concrete.

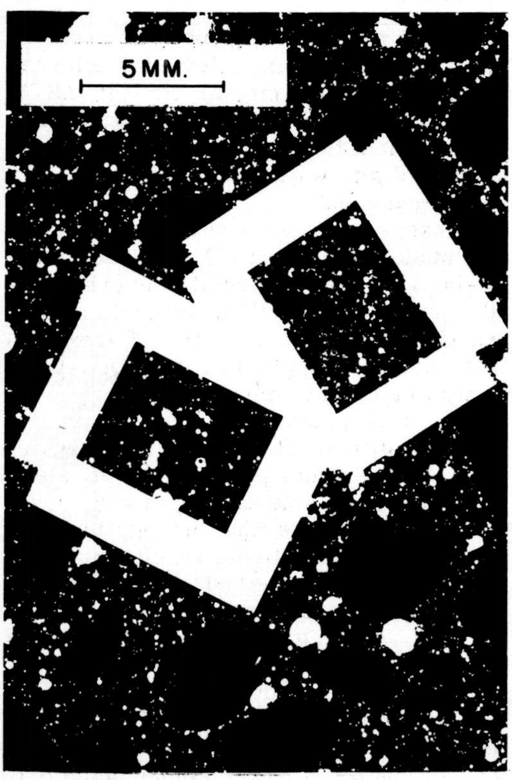

Figure 1. Print of a negative obtained using the plane-intercept method.

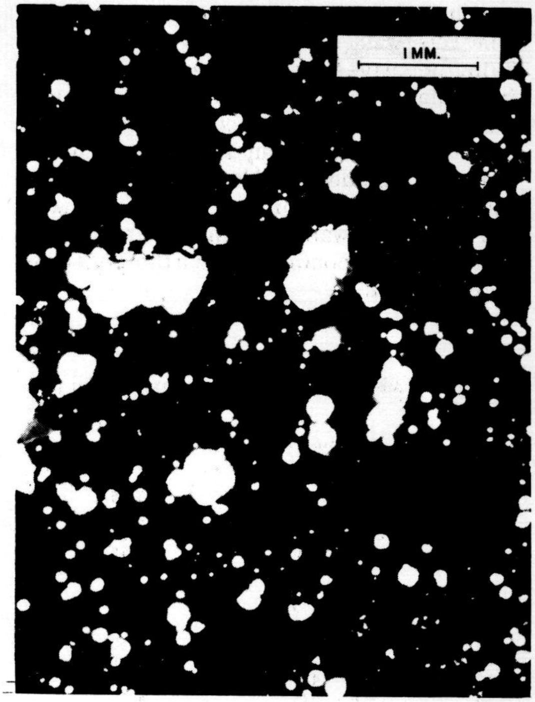

Figure 2. Voids in hardened concrete.

Determination of the Necessary Parameters for Void Analysis

In order to analyze the intercepted voids as they appeared on an interception plane, two items were measured: (1) the size distribution of the circular spots appearing on enlarged photographs and (2) the number of intercepted voids per unit area of concrete.

The size distribution of the circles transcribed on an interception plane was determined by dividing the circles on photographs such as Figure 2 into 15 size classes. The actual size classification of a transcribed circle was accomplished by using a transparent scale on the enlarged image. The size classes used to indicate the size distribution of circles were kept the same, regardless of magnification used. The range and average size of each of the 15 size classes are shown in Table 1. For each void analysis the number of voids appearing on four enlarged photographs were classified and tabulated. Provision was also made in this tabulation for calculating the parameters $[1]_{-1}$, $[1]_{1}$, and $[1]_{2}$.

The number of voids per unit area of concrete was determined from the 5- by 7-in. negatives, which were images of the intercepted voids magnified six diameters. Two negatives were obtained from each concrete for which an analysis of the air voids was made. To determine the parameter n, the number of voids appearing on the negatives was determined and divided by the area of concrete which the negatives represented.

TABLE 1

SIZE CLASSIFICATION OF TRANSCRIBED CIRCLES

Size Class	Range of Size Class	Average Size of Circles in Size Class
	mm.	mm.
1	0 - 0.025	0 0125
2	.025 - .050	.0375
3	.050 - .075	.0625
4	.075 - .100	.0875
5	.100 - .125	.1125
6	.125 - .150	.1375
7	.150 - .200	.1750
8	.200 - .250	.2250
9	.250 - .300	2750
10	.300 - .375	.3375
11	.375 - .450	.4125
12	.450 - .525	.4875
13	.525 - .600	.5625
14	.600 - .675	.6375
15	.675 -.750	.7125

TESTS

Object of the Tests

After developing a satisfactory technique for determining the properties of the air voids in hardened concrete, several types of concrete were made and tested. The object of the tests was primarily to determine the effect of certain variables on void properties.

The scope of the tests performed was not great enough to provide much information on what can be done to control void properties. However, it was shown that void properties may depend on several variables, notably richness of mix and total amount of entrained air.

Variables

Fifteen different types of concrete were made, using two coarse aggregates, two cement contents, various air contents, and two air-entraining agents, in various combinations. The concretes were made by combining these variables as follows:

A. Using crushed dolomite as coarse aggregate,

(a) Cement factor of 4 sacks per cu. yd.,

1. Air contents of approximately 1½, 2, 4, 5½, and 7½ percent obtained by using Vinsol resin.

B. Using natural dolomitic gravel,

(a) Cement factor of 4 sacks per cu. yd.

1. Air contents of approximately 1½, 3, 5½, and 7 percent obtained by using Vinsol resin.

2. An air content of approximately 5½ percent obtained by using Darex AEA.

(b) Cement factor of 7 sacks per cu. yd.,

1. Air contents of approximately 1½, 3, 5½, and 6½ percent obtained by using Vinsol resin.

2. An air content of approximately 5½ percent obtained by using Darex AEA.

Materials

Type I portland cement was used. A brand of cement was selected which gave a low result in the mortar air test (ASTM Designation C185-49T). It was desired to use a cement that would entrain a small amount of air when used without an air-entraining agent.

Vinsol-resin air-entraining solution was made by mixing 20 g. flake Vinsol resin, 3.34 g. commercial sodium hydroxide, and 200 g. distilled water to make a solution of sodium resinate. Darex AEA was used as supplied by the Dewey and Almy Chemical Company.

All aggregates were used in an air-dried condition. Both coarse aggregates used in the tests passed a ⅜-in. sieve. This maximum size aggregate was chosen in order to reduce the photography required to obtain reliable results using the plane-intercept method. The crushed dolomite used contained practically no impurities and had a fineness modulus of 5.83. The natural dolomitic gravel contained 2.5 percent by weight of chert and had a fineness modulus of 5.45. The sand used was composed of approximately 60 percent quartz, the remainder being primarily dolomite including a trace of chert. The fineness modulus of the sand was 2.60.

Test Procedures

All concrete batches were 0.6 cu. ft. in size and were designed by trial and error. Only enough sand was added to any particular type of concrete to provide good workability. Three batches per type of concrete were mixed, each batch on a different day. The sequence of operations for mixing, placing, and curing a concrete batch was as follows:

1. Predetermined amounts of cement, sand, and gravel were added to a counter-current batch mixer and mixed dry for 2 min.
2. The major portion of the mixing water (containing the air-entraining agent when used) was added and the mixing continued.
3. The additional water required to give a 3-in. slump was gaged by eye, making small successive additions during the next 2 to 3 min. The batches were always mixed at least 2 min. after all water had been added and the total wet mixing time was 5 min.
4. The mixed batch was turned over once with a large trowel and measurements were made of slump, unit weight, and air content using the pressure method.
5. Batches which did not have the desired slump or air content were discarded and repeated with a different amount of water or air-entraining agent.
6. The fresh concrete was placed in a lightly-oiled steel mold. The mold had inside dimensions of 3- by 4- by 16- in. and was filled in two equal layers. Each layer was rodded 25 times with a small steel blade 3 in. wide. The excess concrete was then removed by troweling.
7. The molded concrete was covered with wet burlap for one day. At the end of one day the specimen was removed from the mold and immersed in water at 72 F. for 27 days.
8. When the concrete was 28 days old two ½-in. slabs were cut from the 3- by 4-by 16-in. specimen. One 5-by 7-in. negative was obtained from each slab for use in determining the void properties of the concrete.

Void Properties

Table 2 contains a summary of the test results obtained from all tests made. The results listed in the table are the average of the results obtained from the three specimens made for each type of concrete tested.

For convenience in this discussion the types of concrete tested are assigned numbers in Table 2. The significance of the

TABLE 2

SUMMARY OF TEST RESULTS

Concrete Type	A41	A42	A44	A45	A47	B42	B43	B45	B47	B45-D	B72	B73	B75	B77	B75-D
PROPERTIES OF FRESH CONCRETE															
Cement Factor, sacks/cu. yd.	4.00	4.01	4.02	4.00	4.01	4.02	4.00	4.00	4.02	4.01	7.01	7.02	7.01	7.09	7.03
Sand Cont., percent of aggregate	50	49	47.5	45	43	48	46	44	42	44	47	45.5	43.5	41.5	43.5
Net Water - Cement Ratio by wt.	.906	.860	.783	.749	.700	.919	.837	.790	.734	.774	.482	.475	.458	.436	.443
Slump, in.	2.8	2.8	2.7	2.9	3.2	3.3	2.9	3.2	3.1	2.9	3.1	3.3	3.2	3.1	3.0
Unit Weight, lb./cu. ft.	148.2	147.1	145.6	143.9	140.0	145.3	143.2	140.3	138.6	141.1	148.9	146.3	143.1	141.6	142.8
Net Air Cont. (Pressure Meter), %	1.4	2.1	4.1	5.5	7.6	1.5	3.2	5.5	7.2	5.2	1.5	3.1	5.5	6.7	5.3
VOID PROPERTIES															
Spec. Sur. of Voids, sq.mm./cu.mm.	25.6	38.1	32.7	33.1	30.3	23.5	28.3	28.0	31.4	29.1	19.9	35.4	39.4	43.6	39.6
Paste Content of Concrete	.286	.277	.260	.251	.241	.299	.280	.269	.276	.266	.333	.331	.323	.319	.318
Air Content of Concrete, percent	1.43	1.88	4.08	5.02	7.72	1.41	3.15	5.43	7.15	5.18	1.47	3.06	5.39	6.76	5.33
Voids per cu. mm. of Concrete	7.2	70.2	63.5	73.5	79.3	7.5	45.6	67.8	75.7	77.1	6.3	79.1	105.3	167.0	132.0
Average Diameter of Voids, mm.	.1084	.0412	.0628	.0635	.0747	.0936	.0514	.0604	.0760	.0536	.1076	.0499	.0669	.0621	.0567
Void Spacing Factor, mm.	.250	.120	.118	.107	.101	.255	.140	.118	.107	.113	.293	.124	.100	.084	.094

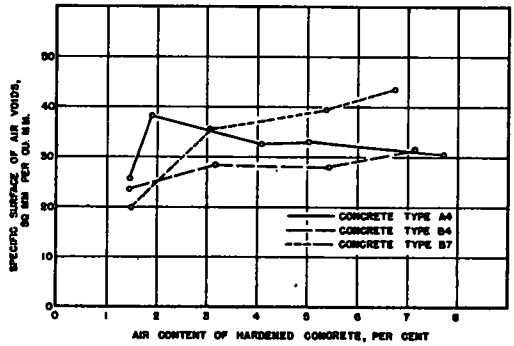

Figure 3. Relationship between air content and specific surface of the voids.

numbers is as follows: (1) The letter preceding a designation number indicates the coarse aggregate used, A indicating crushed dolomite and B indicating natural dolomitic gravel. (2) The first number indicates the cement factor in sacks per cu. yd. (3) The second number indicates the net air content of the concrete within plus or minus 1 percent. (4) The suffix D indicates that Darex AEA was the air-entraining agent used. The absence of D indicates that no air-entraining agent or Vinsol resin was used.

In all cases, there was good agreement between air content as determined on the hardened concrete and air content as determined on the fresh concrete by the pressure method. Usually the difference was less than 0.2 percent air.

Comparing the void properties of concretes B45 and B45-D and concretes B75 and B75-D, it is apparent that there was practically no difference between the void properties of concretes made with Darex AEA and those made with Vinsol resin.

Figure 3 shows the relationship between specific surface of entrained voids and air content as determined by the plane-intercept method. In this and subsequent figures the points plotted were obtained from concretes made by using Vinsol resin or no air-entraining agent. In general, the specific surface of the entrained spheres increased as air content was increased slightly by using Vinsol resin. For air contents greater than 3 percent, the specific surface did not change appreciably for concretes with a cement factor of 4; however, for the concretes with a cement factor of 7, the specific surface increased by a factor of about two as air

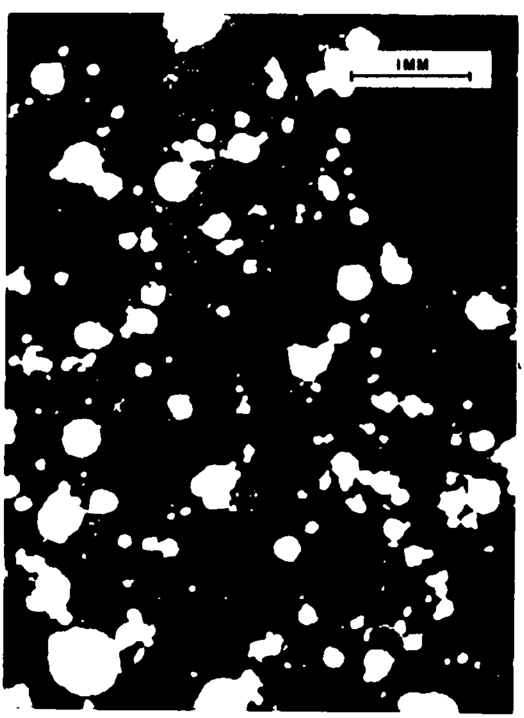

Figure 4. Voids in concrete Type B47.

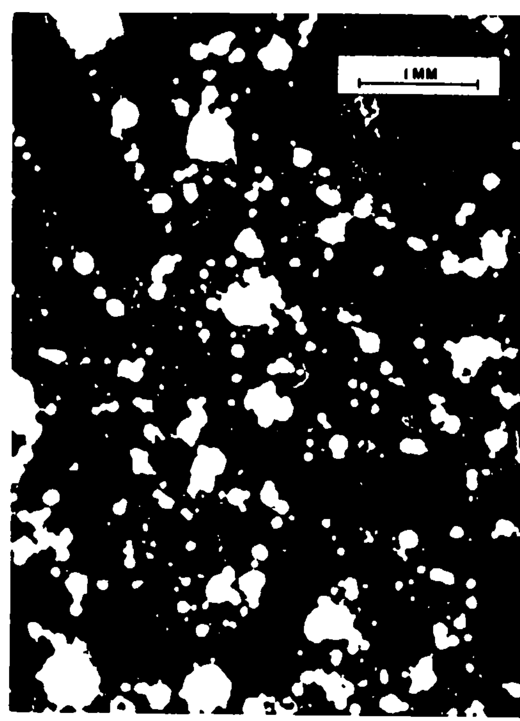

Figure 5. Voids in concrete Type B77.

content was increased from 1.5 to 6.8 percent. The specific surface did not vary significantly between the concretes having different aggregates but the same cement content, except in the low-air-content range.

Figures 4 and 5 are photographs of the voids in concretes B47 and B77, respectively. From the photographs it is readily apparent that for nearly equal, high air contents the voids were more numerous and smaller in the concrete with a higher cement content. These photographs also serve to point out that the voids in concrete occur as independent spheres. In all cases, the voids existing in the concretes tested were well distributed throughout the paste component of the concrete.

From Table 2 it can be observed that the number of voids per unit volume of concrete increased sharply with a small addition of entrained air. It is interesting to note that concrete B77 had 167 voids per cubic millimeter. This is equivalent to 128 billion voids per cu. yd.

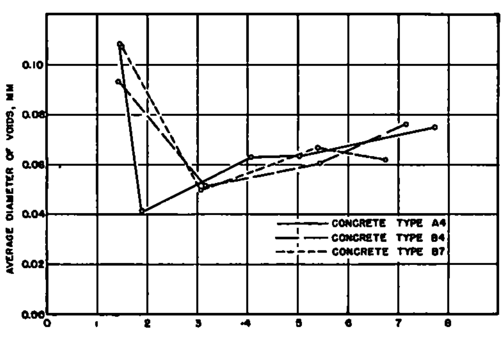

Figure 6. Relationship between air content and average diameter of entrained voids.

The relationship between average diameter of voids and air content is shown in Figure 6. These curves, with the exception of one point, show that the average diameter of the voids in the air-entrained concrete was only slightly affected by cement content and angularity of coarse aggregate when Vinsol resin was used as the air-entraining agent. The average diameter of the voids was a minimum for small additions of entrained air and in the range of air content normally used for air-entrained concrete the average diameter of voids increased slightly with air content.

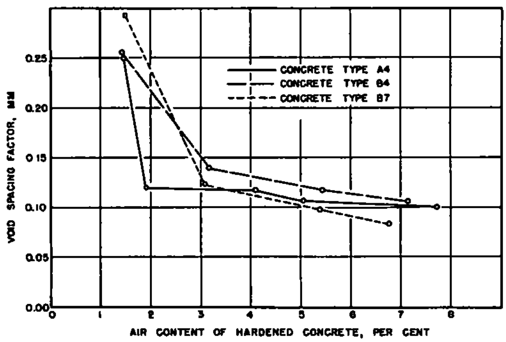

Figure 7. Relationship between air content and void spacing factor.

The information on void properties was used in conjunction with the fractional paste content of the concretes to compute void spacing factor by using Equation 5. The relationship between void spacing factor and air content is shown in Figure 7. The most significant item shown by these curves is that void-spacing factor was decreased by about half when air content was increased just slightly above that obtained without using an air-entraining agent. The curves also show for air contents greater than about 3 percent that (1) void-spacing factor decreased just slightly with a large increase in air content and (2) void-spacing factor was not greatly affected by difference in cement factor and angularity of coarse aggregate.

CONCLUSIONS

1. The plane-intercept method proved to be satisfactory for analyzing the voids in hardened concrete. The time required per analysis is not excessive provided a large number of analyses are carried out together.

2. In all cases, there was good agreement between air content as determined on hardened concrete by the plane-intercept method and air content as determined on the fresh concrete by the pressure method.

3. In all concretes tested, the entrained air existed as small, well-distributed spheres.

4. From the limited tests performed, it appears that voids entrained by Vinsol resin and voids entrained by Darex AEA have about the same characteristics.

5. Specific surface of the voids in the concretes tested ranged from about 20 to 45 sq. mm. per cu. mm. and, in general, showed a marked tendency to increase with a small addition of entrained air. For larger amounts of entrained air, specific surface was not greatly affected by increase in air content for concretes with a cement factor of 4 sacks per cu. yd. However, with a cement factor of 7, specific surface increased with air content within the limits of air content used in the tests.

6. The tests indicate that the average diameter of entrained voids is a minimum for small additions of entrained air. The addition of 1.6 percent entrained air to a 7-sack mix caused average void diameter to change from about 0.11 to 0.05 mm. In the range of air content normally used in air-entrained concrete, average diameter of spheres increased with air content.

7. There were about 5 billion spherical voids per cu. yd. in normal concrete containing 1.5 percent air. A 4-sack mix with about 7½ percent of air contained about 60 billion spheres per cu. yd., and a 7-sack mix with about 7 percent air contained about 130 billion spheres per cu. yd.

8. Void spacing factor varied from about 0.30 to 0.08 mm. and was decreased by as much as one half for very small additions of entrained air. For air contents greater than 3 percent, void-spacing factor (1) decreased slightly with relatively large increases in air content and (2) was not greatly affected by differences in cement factor and angularity of coarse aggregate.

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