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Air-Entrained Concrete
Properties of Air Voids and Service Record of Pavements

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Contents

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

$$[m]_1 = \frac{a_1 m_1 + a_2 m_2 + a_3 m_3 + \text{---}\ a_i m_i}{a_1 + a_2 + a_3 + \text{---}\ a_i} = \frac{\Sigma (am)}{\Sigma a}.$$

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

$$[l]_1 = \frac{a_1 l_1 + a_2 l_2 + a_3 l_3 + \text{---}\ a_i l_i}{a_1 + a_2 + a_3 + \text{---}\ a_i},$$

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

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[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.

$$M = \frac{2n\,[1]_{-1}}{\pi}, \qquad (3)$$

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

$$V_t = \frac{\pi n\,[1]_2}{4}. \qquad (4)$$

5. The void spacing factor[2] is

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

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.

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

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

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.

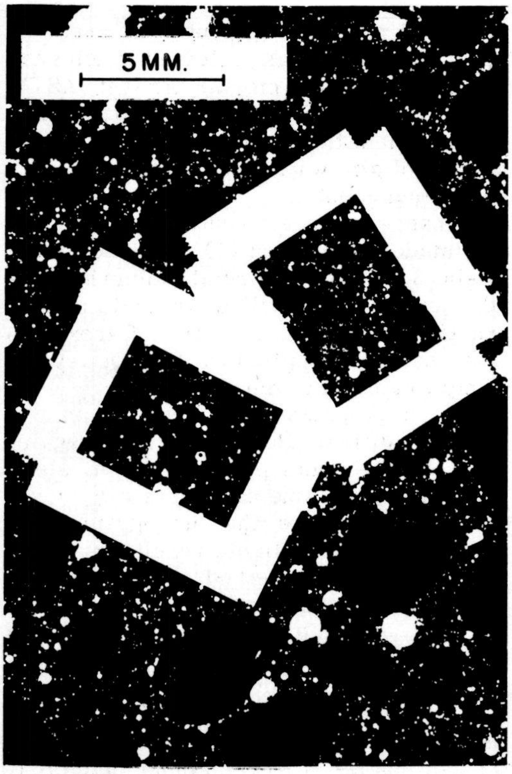

Figure 1. Print of a negative obtained using the plane-intercept method.

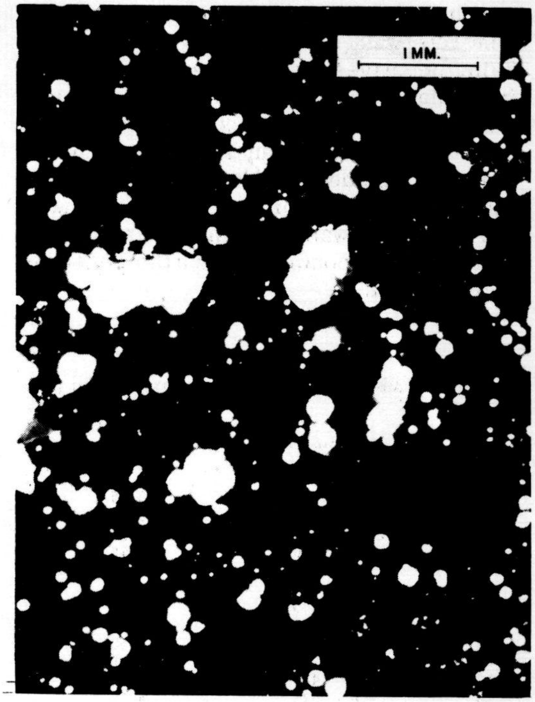

Figure 2. Voids in hardened concrete.

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 $[l]_{-1}$, $[l]_1$, and $[l]_2$.

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

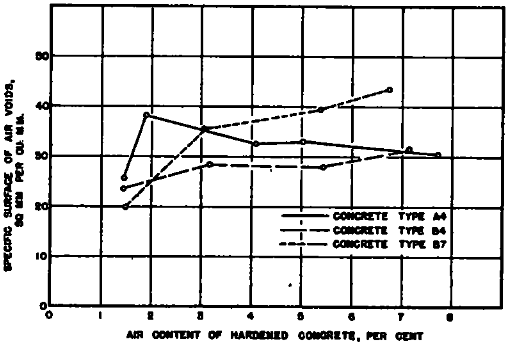

Figure 3. Relationship between air content and specific surface of the voids.

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

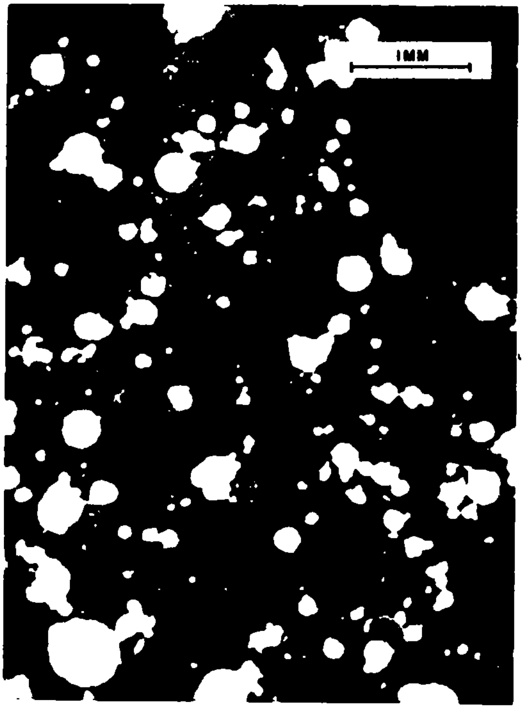

Figure 4. Voids in concrete Type B47.

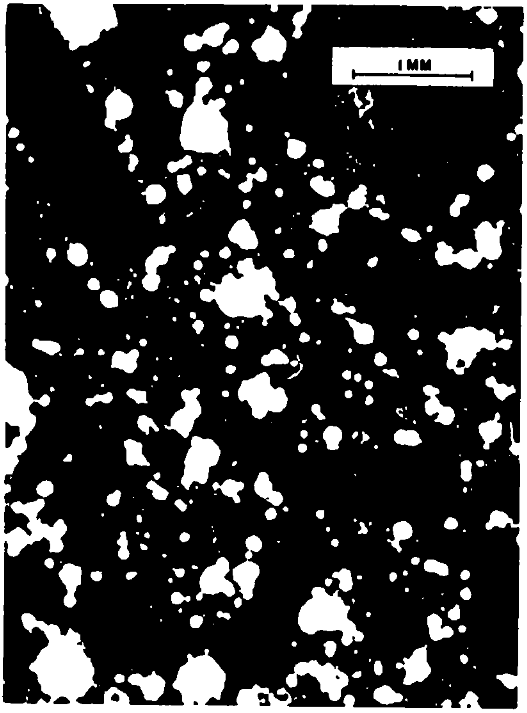

Figure 5. Voids in concrete Type B77.

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.

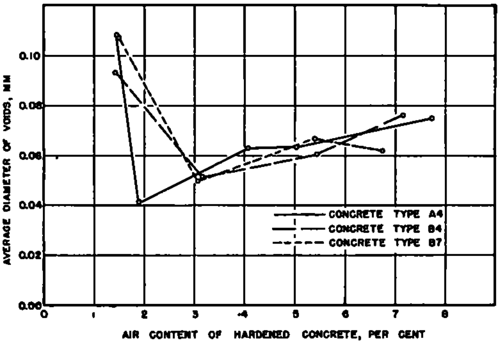

Figure 6. Relationship between air content and average diameter of entrained voids.

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.

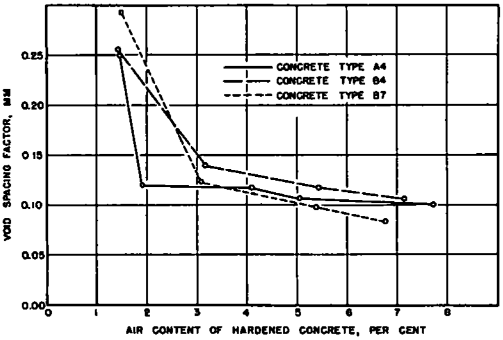

Figure 7. Relationship between air content and void spacing factor.

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.

ACKNOWLEDGMENT

All tests were made in the Materials Testing Laboratory of the University of Wisconsin. Thanks are due to George W. Washa, associate professor of mechanics in the University of Wisconsin, for many helpful suggestions throughout the course of the work.

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Record of Experimental Air-Entrained Concrete 10 to 14 Years After Construction

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THIS paper describes the performance record of 14 concrete test roads in five northeastern states. Built 10 to 14 years ago with a wide range of variables, these roads provide an opportunity to compare the performance of air-entrained concrete with adjacent sections of the same construction but without air entrainment.

High durability and assured resistance to the severe exposure of repeated cycles of freezing and thawing and salt action in ice removal have been given to these concrete pavements over a period of 10 to 14 years by proper air-entrainment in the concrete mixture.

No scaling or disintegration has occurred on any of the air-entrained concrete sections of the 116 lane-miles represented. But on many adjacent sections with cement from the same mill, but without air-entrainment, scaling up to 100 percent of the area has occurred.

The use of coarse-ground normal cement compared with fine-ground cement under the same conditions has not improved the resistance to scaling and disintegration, but with air-entrainment the performance has been outstanding in all respects.

● THE most-important single development in concrete technology of the past two decades is the application of air-entrainment to the mix for the improvement of durability, workability, uniformity, and other important features.

A necessary requirement for concrete of high durability and assured resistance to the most-severe exposure of repeated cycles of freezing and thawing and salt action has been met over the past 12 years or more by proper air-entrainment in the mix. In fact, to date, such assurance has not been generally obtained for pavements in any other way.

This accounts, then, for the almost universal adoption of air-entrained concrete by state, federal, and other large users, especially in the northern states, where high resistance to freezing and thawing as well as salt action in the treatment of icy pavements must be met.

Much has been written on the action of air-entrainment in securing resistance to repeated freezing and thawing. Reduced to a very simple statement, William Lerch says (in "Basic Principles of Air-Entrained Concrete"):

"The presence of these tiny bubbles materially alters the properties of both the plastic mixture and the hardened concrete. The air bubbles serve as reservoirs that accommodate the expansion resulting from the freezing of water within the concrete. As the freezing of the water within the capillaries progresses, the expansion pressure is relieved by forcing the excess water into the air bubbles, where the expansion during freezing can occur without disrupting the concrete. When thawing occurs the air compressed in the bubbles forces the water back into the capillaries. Thus the bubbles continue to serve their purpose during repeated cycles of freezing and thawing."

EARLY TEST ROADS

The earliest use of air entrainment began in the State of New York in 1938 with the inclusion of a test section in one of the paving contracts. This was followed with the building of complete test projects as regular road contracts during 1939 through 1942 in several northeastern states. The performance of these pavements has been closely observed from time to time. Condition surveys were made in 1946 and 1948 for all projects. Now the results from the latest condition survey of the 14 test projects made during 1952 after a period of 10 to 14 years in service forms the basis of this paper. A total of 116 lane-miles of pavement were constructed on these 14 projects, eight of which are in New York State, three in Pennsylvania and one each in Vermont, Maine, and Massachusetts.

In most instances the test roads were built with a wide range of cement variables in respect to air-entraining agents, combinations with natural cement and, in some cases, using fine and coarse ground cements with and without air-entrainment. However, these projects were so constructed that cement was the only variable, in so far as possible. An excellent opportunity was therefore provided to observe long-time pavement performance on adjacent sections of air-entrained and non-air-entrained concrete constructed under identical conditions.

Similar combinations were repeated several times on most of the test projects so as to get a good range in representative results. The various air-entraining agents interground with the portland cements based on percent by weight of cement were: Vinsol resin, 0.03, 0.04, and 0.05 percent; codfish oil, 0.03 and 0.05 percent; beef tallow, 0.05 percent. Also, small amounts of beef tallow or parafin were ground with natural cements used in blends with portland cement, except in one instance where the tallow was purposely omitted from the natural cement.

Most of us know that air-entrainment has done a remarkable job in improving the durability of concrete, but the truly amazing thing is to observe this phenomenon by comparison with adjacent concrete in the same job and in job after job where the only variable is that of air-entrainment in the mix.

It is of vital importance, however, that the air content be maintained above a certain minimum based on the volume of mortar in the mix, which varies with the maximum size and grading of the coarse aggregate. For mixes requiring high mortar content, where small size coarse aggregate is used, the desirable air content is relatively high. But for the usual grading of aggregates used in paving work, the minimum entrained air is set at 3 to 4 percent by most of the northeastern states.

Fortunately for the early test roads discussed in this paper, the amount of air-entraining material used was in the range of 0.03 to 0.05 percent by weight of cement; thus, as it later developed, the air content was sufficient to insure high durability. At the time, however, very little was known about this matter.

It soon appeared that excessively high air contents reduced the strength and made the mix sticky and hard to work without tearing. Present specifications have developed from that point, together with improvements in the form of the air-entraining agent, so that these early troubles have been overcome and high durability is obtained with minimum reduction in strength.

The procedure for measuring air content on these early jobs was limited generally to the weight or gravimetric method, but only a limited number of such tests were made. For example, the approximate air content for concrete made with the various cement combinations on the Maine project was 1.0 percent for non-air-entraining cement, 4.5 percent for 0.03 percent Vinsol resin and about 9 percent for 0.05 percent Vinsol resin, the air-entraining agent being interground with the cement. Subsequent tests made with blends of portland and natural cements have shown an average air content of about 2 percent.

SURVEY PROCEDURE

The following procedures were used in making the current and previous condition surveys: (1) Line diagrams were obtained from the state highway departments showing the locations of all cement sections by lane and stations. (2) Portland Cement Association field sketch sheets, showing each pavement slab, were used for recording the data. (3) The survey was made by walking each roadway and recording observed conditions for each slab.

The information recorded on the sketch sheets included: (1) estimated amount of scaling as a percentage of each slab area; (2) occurrence of D-cracking at slab edges and width of such bands; (3) areas of progressive disintegration; (4) all cracking of whatever nature by approximate location and shape of crack (not continued after the 1948 survey); (5) extent of plus and

TABLE 1

SUMMARY OF AIR-ENTRAINED-CONCRETE TEST-ROAD CONDITION SURVEY-1952

Project	Year Constr	A-E Port Cem't				(A-E) + Nat + Fat				Non AE + Nat + Fat				Non AE + Nat. - Fat				Non AE Port Cem't			
			Slabs Scaled				Slabs Scaled				Slabs Scaled				Slabs Scaled				Slabs Scaled		
		Total Slabs	No	% Total	% Area	Total Slabs	No	% Total	% Area	Total Slabs	No.	% Total	% Area	Total Slabs	No	% Total	% Area	Total Slabs	No	% Total	% Area
1 Northern State Parkway Nassau Co , N Y	1938	2	-	-	-	2	-	-	-	6	-	-	-	-	-	-	-	6	-	-	-
2 Wurtemburg-Wey's Crossing - Dutchess Co , N.Y.	1939	169	-	-	-	-	-	-	-	170	3	1 8	T	-	-	-	-	175	57	32 5	2 7
3. Tupper Lake - Long Lake Hamilton Co , N Y	1939	40	-	-	-	2	-	-	-	778	60	7 7	T	-	-	-	-	-	-	-	-
4. Wawbeck-Saranac Lake Franklin Co , N Y	1939	20	-	-	-	-	-	-	-	904	390	43 2	3 7	-	-	-	-	(a) 6	6	100	95
5 Valley Falls Rensselaer Co., N.Y	1939	10	-	-	-	-	-	-	-	10	3	30	T	-	-	-	-	-	-	-	-
6 Harpersfield-Stamford Delaware Co , N Y	1939	46	(b) 4	covered		-	-	-	-	904	(c) 711	78 6	(d) 9 2	-	-	-	-	(e) 20	20	100	-
7. West Point-Cornwall Orange Co , N Y	39-'40	150	-	-	-	414	-	-	-	458	9	2 0	T	-	-	-	-	206	146	71	13 8
8. Scarboro-Portland Maine	39-'40	469	-	-	-	-	-	-	-	192	6	3 1	T	-	-	-	-	195	191	98	50
9 Leg Route 84 Sec 10 Crawford Co , Pa	1940	140	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	210	200	95	28.3
10. Leg Route 200 Sec 3 Warren Co , Pa	1940	128	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	180	20	11 1	1 6
11 Hope Center-Wells Hamilton Co., N Y	1940	179	(f) 3	covered		-	-	-	-	302	(g) 277	91.8	(h) 32 5	178	(i) 178	100	(j) 67 8	21	(k) 21	100	(l) 59 2
12. State Line-W. Stockbridge Mass.	1940	105	-	-	-	4	-	-	-	109	-	-	-	-	-	-	-	112	-	-	-
13. Montpelier-Barre Vermont	1941	23	(b) 1 5	covered		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14 Leg. Route 271 Sec 4 Crawford Co , Pa	1942	192	-	-	-													202	147	727	10 7
	Avg. Age 12¼ Yr	Total Slabs 1673 Slabs Scaled - % of Total -				422 - -				3833 1459 38				178 178 100				1333 808 60			

NOTE T = Trace of scale (less than 1 percent)
(a) Includes 4 slabs surface treated
(b) Surf treated due to frost heave and cracking
(c) Includes 513 slabs or 57 percent surf treated 1946, due to scaling
(d) Based on uncovered slabs only This would be 60 7 percent if covered slabs are 100 percent scaled
(e) Scaled heavily and surf treated
(f) Surf treated due to heavy rain wash when built
(g) Includes 75 slabs or 25 percent surf treated since 1948 due to scaling
(h) Based on uncovered slabs only This would be 49 5 percent if covered slabs are 100 percent scaled.
(i) Includes 156 slabs or 87 6 percent surf treated since 1948 due to scaling
(j) Based on uncovered slabs only This would be 96 percent if covered slabs are 100 percent scaled.
(k) Includes 2 slabs or 9 5 percent surf treated since 1948
(l) Based on uncovered slabs only This would be 63 percent if covered slabs are 100 percent scaled.

minus grades, cuts and fills, grade points at cut and fill runouts, wet ditches, frost heave and settled areas, all bridges, important culverts, road intersections and any faulting at joints; and (6) stations for all cement changes and other critical points including locations where photographs were secured.

All of these data were carefully studied for any relationship to structural and surface conditions. Most of the cracking is easily traced to subgrade conditions, drainage, frost heave, settlement, normal contraction, and restraint at fixed structures (such as catch basins and manholes). There appears to be no relationship between cracking and cement variables even in the case of the Main project where low 28-day strengths occurred for the high-air-content sections first constructed.

RESULTS FROM CONDITION SURVEY 1952

A comparison of results for all cement variables on the 14 test roads is shown in Table 1. There is no scaling or disintegration D-cracking on any of the sections using air-entraining portland cement or the blend of air-entraining cement with natural cement. It will be noted, however, that scaling has occurred to a considerable extent with other cement variables: (1) blend of portland with natural cement containing fat, 38 percent of slabs; (2) non-air-entraining portland cement, 60 percent of slabs; and (3) blend of portland cement and a natural cement with fatty material omitted, 100 percent of slabs.

These 14 test roads were constructed in 5 states over a 4-yr. period with a large variety of aggregates and cements. The extreme locations geographically are separated by 500 mi. There is, however, one relationship which has held constant throughout all of these projects: the record of uniformly high durability and resistance to all scaling and D cracking wherever air-entraining portland-cement concrete was used.

The contrasts in performance of air-entrained and non-air-entrained concrete are shown in Tables 1 to 4 and Figures 1 to 12.

Table 2 shows the scaling record by years for the cement variables on Route 30, Hope Center-Wells, Hamilton County, New York, 6.20 mi. in length, constructed in 1940. There is no scaling on any of the air-entrained concrete after 12 yr. Note that scaling developed extensively during the first year on all non-air-entrained concrete. Scaling has now progressed to the point where 35 percent of the entire project has been covered with a bituminous surface treatment since the survey of 1948.

TABLE 2

PERFORMANCE RECORD BY YEARS

Route 30 Hope Center-Wells, Hamilton County, New York
Constructed 1940

Cement	Total Slabs	Percent Scaled Area by Years[b] 1941	'43	'46	'48	'52
Non. A. E. + 0.03% Fish Oil[a]	179	--	--	--	--	--
Non. A. E. + Nat. + Fat (1)	302	14.1	15.0	24.2	31.4	49.5
Non. A. E. (2)	21	19.3	21.7	42.0	54.5	63.0
Non. A. E. + Nat. - Fat (3)	178	37.6	48.5	70.0	84.5	96.0

Note--35% of pavement has been surface treated since 1948 because of scaling as follows:
(1) 75 slabs (2) 2 slabs (3) 156 slabs.

[a] 3 slabs surface treated because of heavy rain wash.

[b] Based on 100% scale for covered slabs.

Figure 1 shows Route 30, Hope Center-Wells, N. Y., Station 503 + 41. The slab on near side of transverse joint is non-air-entraining portland cement with 100 percent scale. The lane on right is non-air-entraining blend of portland with natural cement severely scaled and surface treated. The lane on left ahead of joint is air-entrained concrete and shows no scaling here or elsewhere on this project. The same brand of portland cement was used throughout.

Figure 2 shows Hope Center-Wells project, Station 540 + 90. The slabs on near right and far left are air-entrained concrete (0.03 percent fish oil) and show

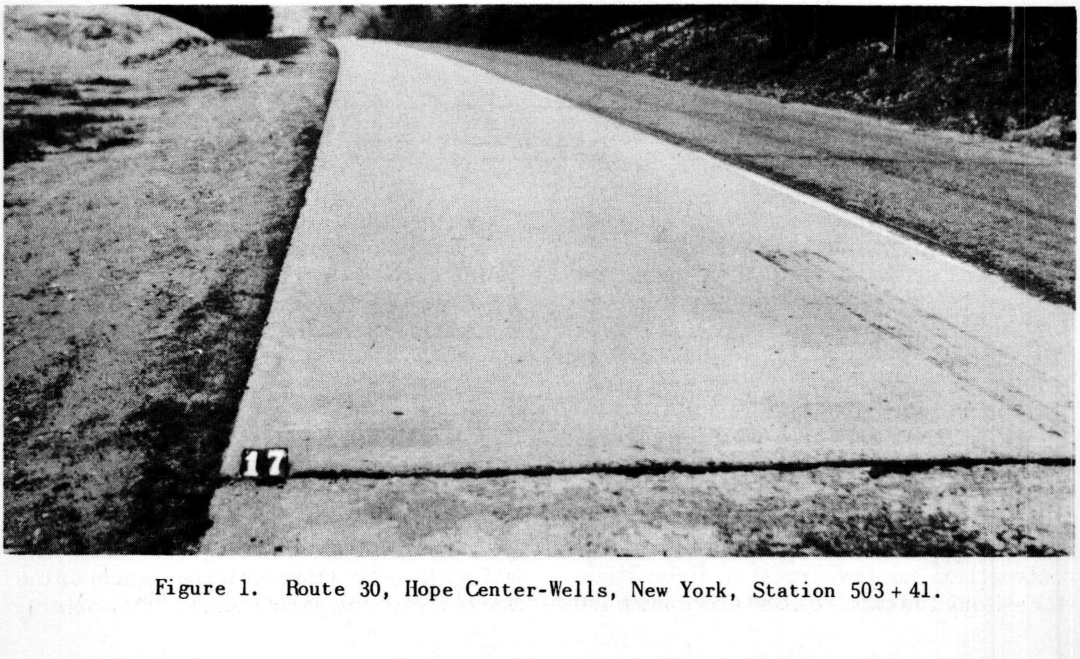

Figure 1. Route 30, Hope Center-Wells, New York, Station 503 + 41.

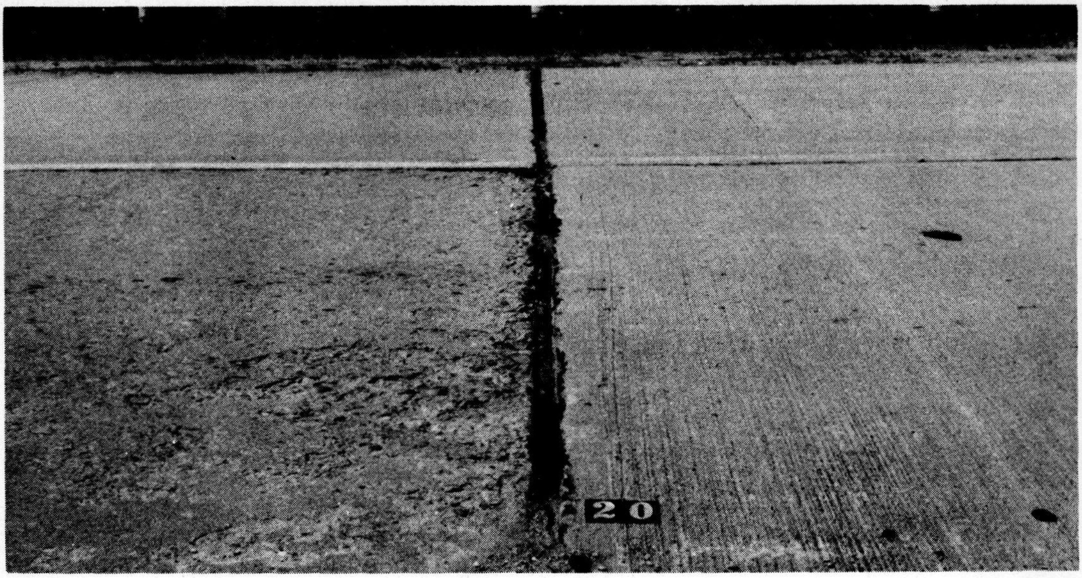

Figure 2. Route 30, Hope Center-Wells, New York, Station 540 + 90.

no scaling. The slabs on near left and far right were made with blends of non-air-entraining portland cement and a natural cement containing fat. This combination scaled for 49.5 percent of the total area.

Figure 3 is also on the Hope Center-Wells project, Station 578 + 00. The lane on right is air-entrained concrete showing no scale throughout. The lane on left is a blend of non-air-entraining portland cement with a natural cement showing 100 percent scale in this area. The two portland cements came from the same mill and are identical except for the air-entraining agent in the one which resisted scaling.

Figure 4 shows Route 23, Harpersfield-Stamford, Delaware County, N. Y., 8.30 mi. in length, constructed in 1939, Station 1337 + 00, showing air-entrained concrete in right lane with no scaling and concrete made with a blend of non-air-entraining portland cement and a natural cement in

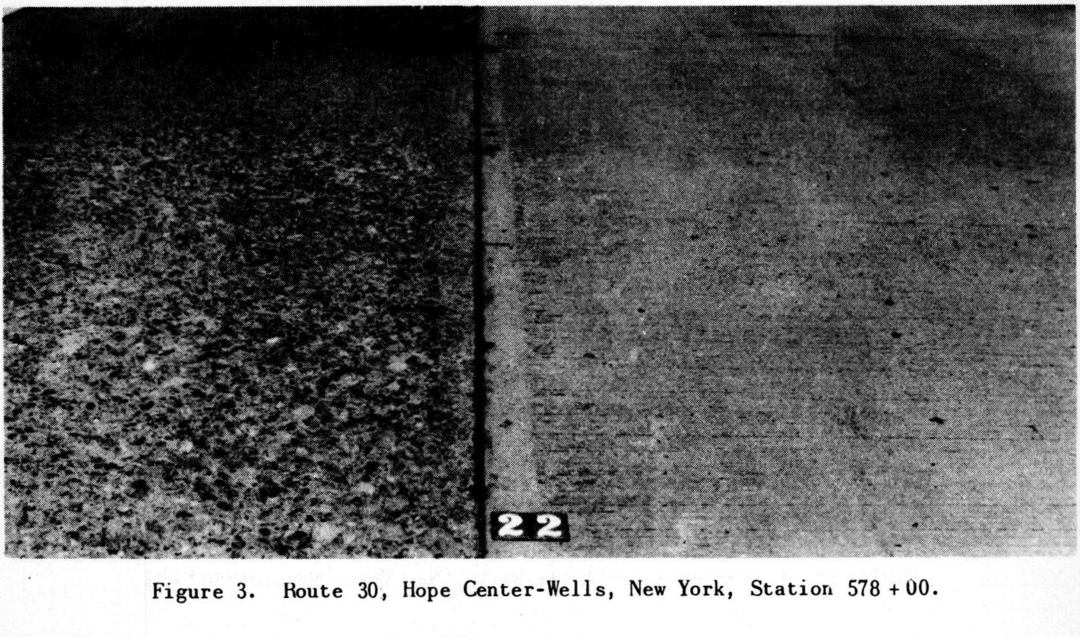

Figure 3. Route 30, Hope Center-Wells, New York, Station 578 + 00.

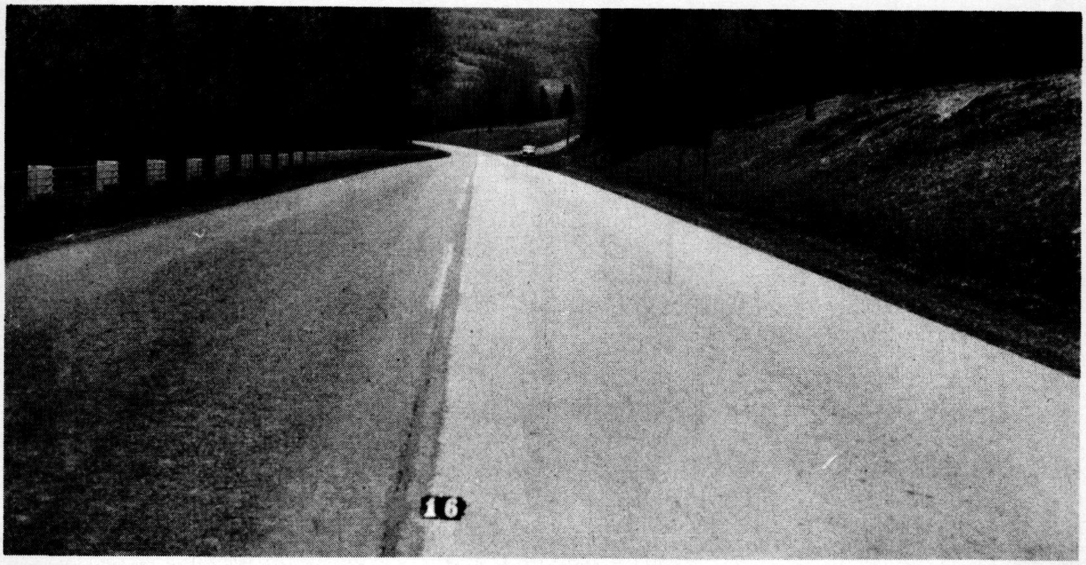

Figure 4. Route 23, Harpersfield-Stamford, New York, Station 1337 + 00.

left lane, now surface treated because of excessive scaling. Portland cement from the same mill was used in both lanes.

D-cracking, a forerunner of disintegration, has not occurred on any of the air-entrained concrete sections of these test roads nor has it been observed on any air-entrained concrete elsewhere throughout the northeast. This form of disintegration has occurred, however, on many of the test road sections where air-entrainment was not used. A typical example of this trouble is shown in Figure 5.

Figure 5 shows Route 146, Mechanicville-Clifton Park, Saratoga County New York, constructed in 1948 with non-air-entrained concrete. Severe D-cracking has occurred in wide bands as indicated. This type of defect is usually progressive, as may be seen in Figure 10.

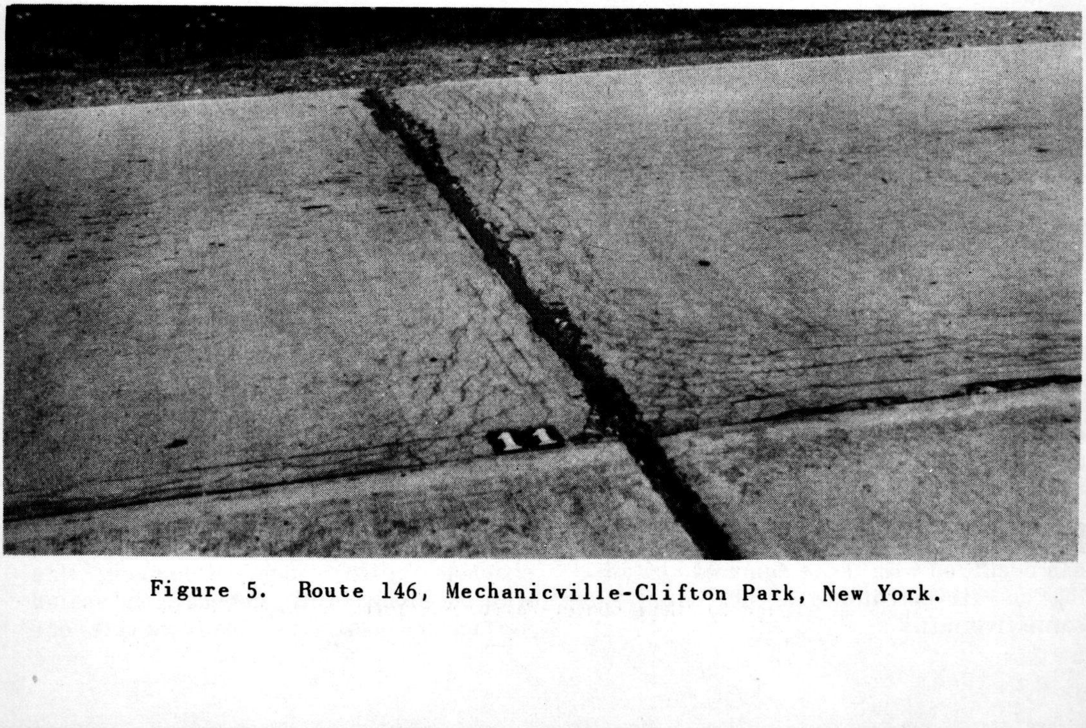

Figure 5. Route 146, Mechanicville-Clifton Park, New York.

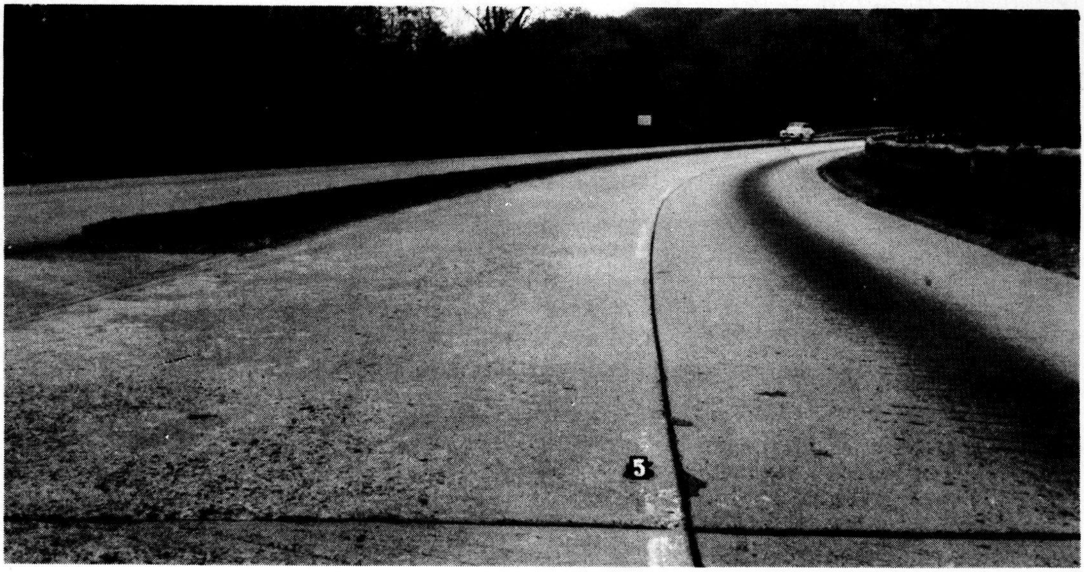

Figure 6. US 9, West Point-Cornwall, New York, Station 195 + 35.

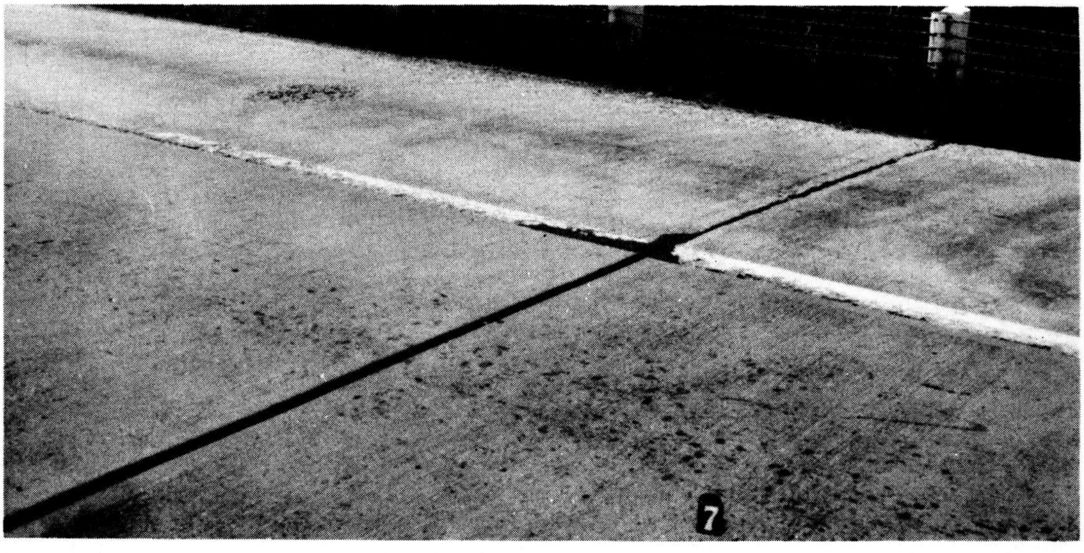

Figure 7. Route 9G, Wurtemburg-Wey's Crossing, New York, Station 211 + 60.

Figure 6 shows US 9W, West Point-Cornwall, Orange County, New York, 5.30 mi. in length, constructed in 1939-40. Station 195 + 35, showing air-entrained concrete in lane on right with no scale and non-air-entrained concrete with 70 percent scaled area on left lane. Of the non-air-entraining portland-cement-concrete slabs, 71 percent have scaled, while no scaling has occurred with these cements containing an air-entraining agent, from the same five mills.

Figure 7 is of Route 9G, Wurtemburg-Wey's Crossing, Dutchess County, New York, 4.5 mi. in length, constructed 1939, Station 211 + 60. The slabs in near lane were built with air-entraining portland cement (0.05 percent tallow) and show no scaling here or throughout the job. Note the excellent slab edges at transverse joint. This is typical of air-entrained concrete performance. Compare this with the sloughed off joint edges and scaled surface of non-air-entrained concrete sec-

Figure 8. US 1, Scarboro, Maine, Station 243 + 30.

tion in far lane where 32.6 percent of the slabs show scaling in some degree.

Another outstanding contrast in durability between air-entrained and non-air-entrained concrete is that on US 1, Scarboro, Maine, constructed in 1939 - 40, where all portland cement was made at the same mill. In the 13 years since construction, 50 percent of the entire surface of the non-air-entrained concrete sections, 1.50 mi. in length, has scaled severely with extensive deep disintegration at many joints and slab corners as shown in Figure 8. However, on the 3.50 mi. of air-entrained concrete there is no scaling whatever. Aggregates came from the same source and the same engineer supervised the construction.

Figure 8 shows US 1, Scarboro, near Portland, Maine. The right widening lane, curb and gutter 6.5 mi. in length, were constructed in 1939-40 with non-air-entraining cement, a natural blend and air-entraining cement, Station 243 + 30. The pavement shown in this slide is a section of non - air - entraining cement concrete badly scaled and disintegrated. Of the non-air-entraining cement-concrete slabs, 98 percent are scaled for 50 per-

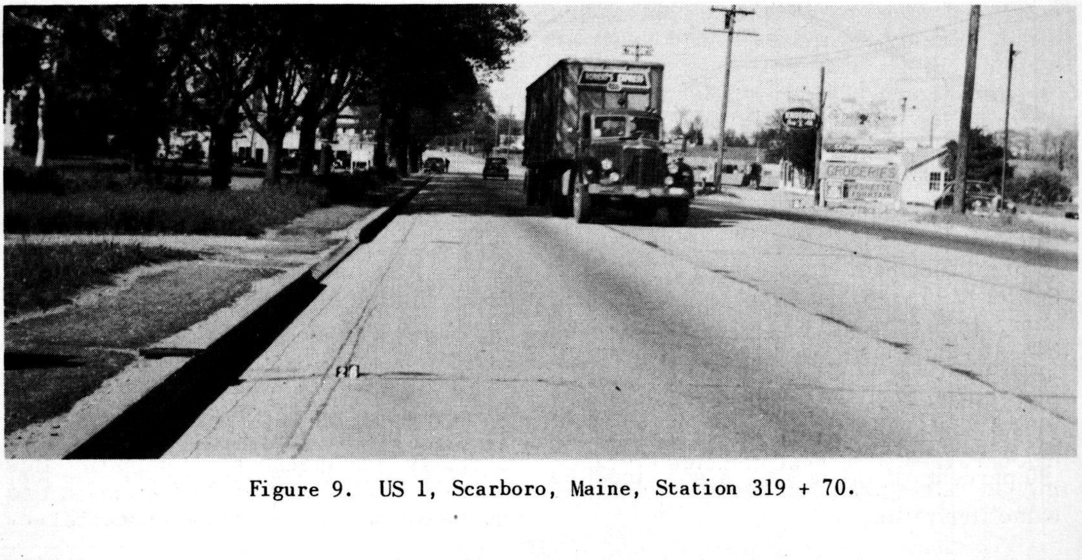

Figure 9. US 1, Scarboro, Maine, Station 319 + 70.

cent of their area. This section was resurfaced in 1952.

Figure 9 shows US 1, Scarboro, Maine, Station 319 + 70. The left widening lane with curb and gutter was constructed in 1939 with portland cement interground with 0.05 percent Vinsol resin. There is no scaling on this or subsequent sections constructed in 1939-40, using 0.03 percent Vinsol resin. All design and construction conditions were identical with those shown in Figure 8, except air entrainment.

Another comparison of performance is that between the fine- and coarse-ground cements, with and without air entrainment, which may be seen on Legislative Route 84, Section 10, (Traffic Route US 6), Crawford County test road at Meadville, Pennsylvania, as shown in Table 3. Available data on the specific surface and mortar air tests for the cement are given for this project.

Some engineers have felt that coarse-ground cements would give superior performance, but after 12 yr. there is no choice on this project between any of the cements either finely or coarsely ground without air-entrainment as both have shown marked defects. However, with entrained air both types of cement have produced concrete which appears as good today as when constructed.

Furthermore, D-cracking followed by disintegration of concrete at about 60 percent of all transverse joints has occurred on the non-air-entrained sections of this project. The D-cracking had reached an advanced stage by 1944. The slab edges at all joints of the air-entrained concrete are in perfect condition today, as may be seen in Figure 11. As a matter of further interest on this project, all of the five cement types were made in the same mill.

Table 3 is a summary performance record of fine-ground versus coarse-ground cements with and without air-entrainment of Legislative Route 84, Section 10, (Traffic Route US 6) Meadville, Crawford County, Pennsylvania, constructed 1940. Note that the coarse-ground non-air-entraining cement gave no better durability than the fine-ground non-air-entraining cement. In both cases about 95 percent of the slabs scaled for nearly 30 percent of the area. Also, about 60 percent of slab ends at expansion joints show severe D-cracking and disintegration. However, there is no scaling or D-cracking on any of the air-entrained concrete sections using either fine- or coarse-ground cement.

TABLE 3

SUMMARY PERFORMANCE RECORD FINE-GROUND VS. COARSE-GROUND WITH AND WITHOUT A-E
Leg. Route 84 Sec. 10, Meadville, Crawford Co., Pa Constructed 1940

Cement	Spec Surf.	Mortar Air	Total Slabs	Slabs Scaled		% Area Scaled
				No	%	
A-1 Non A E fine[a]	1885	3.1	70	68	97	29.7
B-1 " coarse[a]	1340	6.2	70	65	93	26.2
C " fine (N.J.)[a]	1898	--	70	67	96	29.1
A-2 Non A E fine + 0.05 V R	1863	15.8	68	--	--	--
B-2 " coarse + 0.05 V R.	1360	15.8	72	--	--	--

[a] About 60 percent of slab ends at expansion joints show severe D-cracking and disintegration for all three non-air-entraining cements There are no such defects where air-entraining cement was used

Figure 10 is of Legislative Route 84, Section 10, Crawford County, Pennsylvania, 2.50 mi. in length, constructed 1940, Station 85 + 52. This is fine-ground non-air-entraining cement section showing extensive scaling. Disintegration at joints started with D-cracks in wide bands. This type of disintegration has occurred at about 60 percent of joints on both fine- and coarse-ground non-air-entraining cement sections, but all air-entrained sections here, or elsewhere, show none of this trouble.

Figure 11 is of Legislative Route 84, Section 10, Crawford County, Pennsylvania, Station 132 + 23. This is fine-ground air-entraining cement section typical of all such sections on this project. There is no scaling. Slab edges at joints are sound and durable throughout where air-entrained concrete was used.

Figure 12 shows Legislative Route 271, Section 4, (Traffic Route 8), Hydetown - Centerville, Crawford County, Pennsylvania, 3.80 mi. in length, constructed 1942, Station 517 + 50. The A-2 slab on right was made with fine-ground air-entraining cement and shows no scaling throughout the project. The B-1 slab on left was made with coarse-ground non-air-entraining cement and shows about 12 percent scaled area throughout the job.

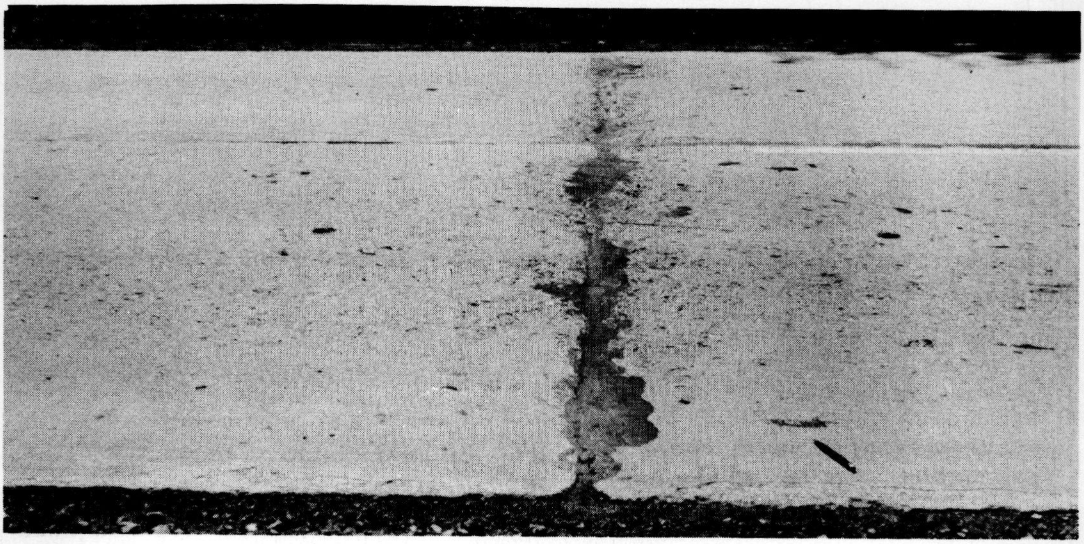

Figure 10. Legislative Route 84 Sec. 10, Meadville, Pennsylvania, Station 85 + 52.

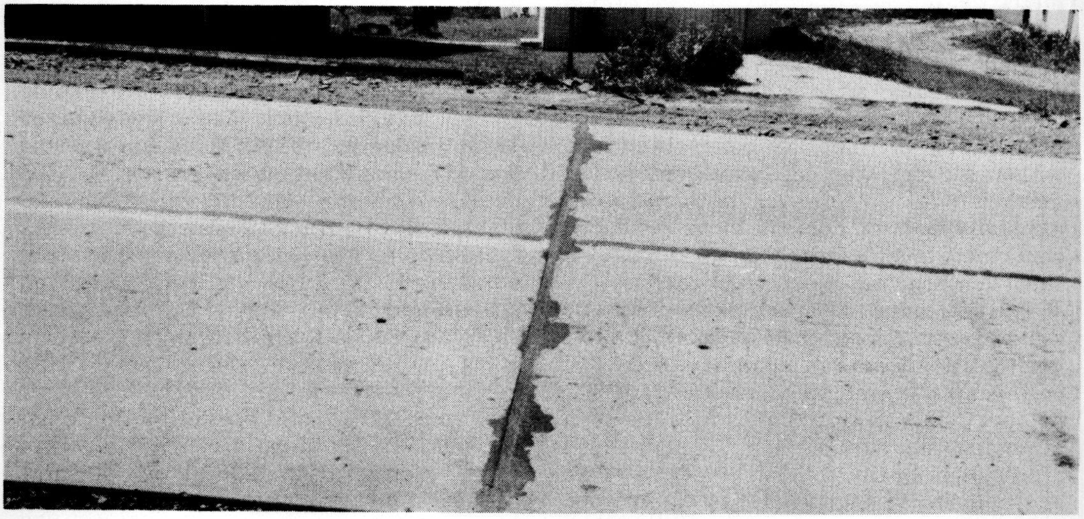

Figure 11. Legislative Route 84 Sec. 10, Meadville, Pennsylvania, Station 132 + 23.

TABLE 4

SUMMARY OF SURFACE CONDITIONS ON THE 14 PROJECTS

Cement	Total Slabs	Slabs Scaled		%Area Scaled
		No.	%	
Air Entraining	1673	--	--	--
A-E + Nat. + Fat	422	--	--	--
Non A. E. + Nat. + Fat	3833	1459	38.0	19.2
Non-Air-Entraining	1333	808	60.6	17.5
Non A. E. + Nat. - Fat	178	178	100.	96.0

Note: 56 mi. of pavement from one to four lanes in width, or 116 lane-miles, are represented.

Table 4, summarizes the performance data given in Table 1 for the 14 test roads. Note that only air entrainment furnished complete protection against scaling, while the non-air-entrained sections showed scaling for 38 to 100 percent of the slabs.

CONCLUSION

During the 14 yr. since construction of the first test section of air-entrained concrete in New York state, the record

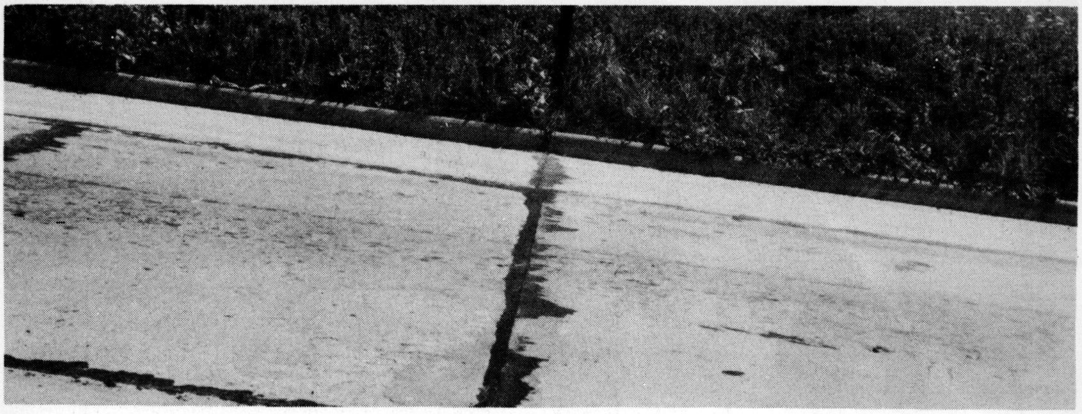

Figure 12. Legislative Route 271 Sec. 4, Centerville, Pennsylvania, Station 517 + 50.

for millions of square yards of this type of concrete has shown outstanding performance. There has been no scaling or D-cracking on any air-entrained concrete where the amount of air actually entrained has been equal to or greater than the minimum amount established for durability.

Air-entrainment is now required in concrete pavements by at least 29 state highway departments, and it is used, under certain conditions, in 10 other states.

Continued experience with the excellent durability of air-entrained concrete under the severe conditions of exposure in the northeast furnishes an outstanding and gratifying performance record in an area where scaling has otherwise been extensive.

This is the story and the record of the 14 air-entrained-concrete test roads in the northeastern states. It is a good record and has served well as the trail blazer for the present wide-spread use of air-entrained concrete in the northeast and throughout the nation.

Discussion

WILLIAM LERCH, Head, Performance Tests Group, Research and Development Laboratories, Portland Cement Association. The author is to be commended for his paper showing the superior performance of air-entrained concrete pavements. It provides one of the most comprehensive reports on the service record of air-entrained concrete available to date. The composition and fineness of the cements used on these experimental projects were not included in the paper. It is believed that many readers will be interested in having this information and that these data will be of value to state highway departments and other agencies responsible for writing specifications for portland cement.

The Research Laboratories of the Portland Cement Association made chemical analyses and fineness determinations of the cements used on seven of the experimental projects. The results of these tests are shown in Table A, together with an identification of the projects where they were used. A few of the cements were used on more than one project and that is shown by the identification of the cements in the table.

The cements used on the seven projects were made at thirteen different plants in Maine, New York, Ohio, and Pennsylvania. They were made from a wide variety of raw materials and represent a relatively wide range in chemical composition and fineness. They include cements that meet the chemical requirements of ASTM Types I and II. Some of the cements were made to meet the special requirements of the then-current specifications of the New York State Department of Public Works, the New Jersey State Highway Depart-

TABLE A

CHEMICAL COMPOSITION, CALCULATED COMPOUND COMPOSITION, AND FINENESS OF CEMENTS USED IN EXPERIMENTAL PAVEMENT PROJECTS

Cement Identification	Air Entraining Agent	ASTM Type	Spec. Surf. Wagner cm.^{2}/g	Oxide Analyses - %						Free CaO	Calculated Compound Composition - %			
				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3		C_3S	C_2S	C_3A	C_4AF
DUTCHESS COUNTY, N Y , R.C. 4016, S.H 8511 - CONSTRUCTED IN 1939														
A	None	II	1835	23.09	4 73	3.45	64.62	1.19	1.43	0.40	45 1	32.3	6.7	10.5
	Tallow	IIA	1740	23.65	4 39	3 25	64.53	1 09	1.34	0.37	43.4	35.1	6.1	9 9
B	None	II	2015	22.78	4.77	3.46	64.92	1.32	1.30	0.62	47 9	27.3	6 8	10.5
	Tallow	IIA	1825	22 69	4.87	4.10	64.51	1.27	1.26	0 08	47.6	29 2	6 0	12.5
C	None	I	1730	21.81	5 58	3.85	63 47	1.46	2.09	0.18	42 9	30.3	8.3	11.7
	Tallow	IA	1480	21.79	6.12	3.98	63.36	1.56	1 60	0.16	40.2	32.2	9.5	12 1
D	None	I	1745	20.35	7.05	2.49	63.51	2.65	2 01	0 32	45.9	23 8	14.5	7.6
	Tallow	IA	1775	20.33	6.95	2.60	63.33	2.60	1.93	0.24	46 4	23 4	14.0	7 9
E	None	I	1970	20.54	6.62	2 42	62 68	3.33	1.90	1.64	39.0	29.6	13 5	7 4
	Tallow	IA	1775	20.58	6 65	2.41	62 53	3.34	1.70	1.58	38.7	29 9	13.6	7 3
F	None	I	1810	20.98	6.85	2 43	62.75	3 52	1.71	0 64	39.0	30.8	14.0	7.4
	Tallow	IA	2010	21.18	6.42	2.40	62.96	3.61	1.61	0 59	41.7	29.3	13.0	7 3
G	None	I	2120	20 35	6.15	3.58	63 65	2 54	1 74	0.72	50.1	20.7	10 3	10 9
	Tallow	IA	2340	19.95	6.42	3.46	63.95	2.52	1.65	1.78	48.6	20.6	11.2	10 5
H	None	I	1950	20.73	6 83	2.41	63.08	2.89	2.11	0.40	42.2	27.7	14 0	7.3
	Tallow	IA	1950	20 57	6.81	2.51	63.01	3 01	1.83	0 78	42.4	27 1	13.8	7.6
ORANGE COUNTY, N.Y., R C. 4027, S.H. 8500 (STORM KING BY-PASS) - CONSTRUCTED IN 1939														
I	None	II	2030	22.66	5.23	3.73	63.90	1.58	1 59	Tr.	42 8	32.7	7 6	11.3
	Vinsol Resin	IIA	1900	23 14	4.91	3 57	63.99	1 62	1 44	"	42.4	34.5	7.0	10 9
F	None	I	1790	21.01	6 73	2.39	62.75	3 56	1 64	0.75	39.3	30.6	13.8	7 3
	Vinsol Resin	IA	1850	21.22	6 79	2.39	62.83	3.56	1.61	0.53	38 7	31 8	14 0	7.3
G	None	I	2075	20 17	6.21	3.57	63.88	2.46	1.65	0 88	51.6	19 0	10.4	10.9
	Vinsol Resin	IA	1930	20.22	6.45	3 47	63 85	2 51	1 65	0 99	49.2	21.0	11 2	10.6
J	None	II	1995	22.15	4.69	2 64	63.68	3.31	1 46	0.40	49.8	26.1	8.0	8 0
	Vinsol Resin	IIA		(Made from the same clinker)										
A	None	II	1720	22.21	4 76	3.74	64 99	1.15	1.43	0.74	51 3	25.1	6.3	11 4
	Vinsol Resin	IIA	1820	21.09	5.17	4.19	64 96	1 22	1.56	0.98	54.9	19.1	6.6	12 7
I	None	II	2045	25.42	4.36	3 21	62.46	1.65	1 55	Tr.	22.7	55 8	6 1	9.8
MAINE EXPERIMENTAL PROJECT F.A. 118AB(2) - CONSTRUCTED IN 1939														
G	None	I	1460	21 24	5 86	2 60	63 59	3 00	1.80	-	49 4	23.3	10 6	8.2
	Vinsol Resin	IA		(Made from the same clinker)										
W STOCKBRIDGE, MASS. EXPERIMENTAL ROAD - CONSTRUCTED IN 1940														
A	None	II	1615	22.35	5.18	3.74	64 38	1.27	1.58	0.54	45.4	29.8	7.4	11.4
	Vinsol Resin	IIA	1820	22 96	5.07	3 29	64.37	1.27	1.60	0.51	42.2	34.0	7.9	10.0
HOPE CENTER WELLS, N.Y., R.C. 4079 - CONSTRUCTED IN 1940														
E	None	I	2000	21.68	5 17	3.97	63.95	1.87	1 67	0.55	50.5	25.4	7.0	12.0
	Codfish Oil	IA		(Made from the same clinker)										
(CEMENTS WITH VARIED FINENESS)														
WARREN COUNTY, PA., ROUTE 200 - CONSTRUCTED IN 1940														
K Normal	None	I	1945	21.16	6.53	2 92	63.72	1 80	1.75	0 61	43.1	28.1	12.4	8.9
K "	Tallow	IA	1990	21.13	6.48	3.00	63.48	1.81	1.74	0.44	43 3	27.9	12.1	9.1
K Special	None	II	1910	22.29	5 49	4.07	62 72	2 33	1.46	0.16	38.4	34.9	7.7	12.4
L Coarse	None	I	1495	22.63	5 09	2.80	64.03	2.28	1 54	1.12	41.6	33.5	8 8	8 5
L "	Tallow	IA	1445	22 59	5.02	2.89	63.85	2 28	1 60	1 09	41.4	33.5	8.4	8.8
CRAWFORD COUNTY, PA, F.A. 298-C, ROUTE 84 - CONSTRUCTED IN 1940														
M Normal	None	I	1940	20.72	5.87	3.11	63 39	2 88	1.90	1.00	47 3	23.7	10.3	9.5
M "	Vinsol Resin	IA	1920	20.66	5 95	3 13	63 29	2.92	1.77	1 12	46.6	24 1	10.5	9.5
M Coarse	None	I	1475	20.74	6.04	3.05	63 65	2.96	1 77	1 24	46.5	24 4	10.9	9.3
M "	Vinsol Resin	IA	1385	20 82	6.01	3.04	63.71	2.92	1.73	1 19	46.7	24.5	10.8	9.3
M Special	None	II	1960	21.81	5.33	4.38	63 36	1 48	1 71	0.86	41 8	31.0	6.7	13.3

ment, and the New York Board of Water Supply. One cement, with a high silica content, was a special product made for use on one of the experimental projects. Cements of normal fineness and coarse-ground cements, 1,385 to 1,495 sq. cm. per g., turbidimeter method, were used on two of the projects, Crawford County and Warren County, Pennsylvania.

The range in some of the chemical constituents and in the fineness of the cements was as follows:

SiO_2 content - 19.95 to 25.42 percent
MgO " - 1.27 to 3.61 "
C_3A " - 6.0 to 14.5 "
C_3S " - 22.7 to 54.9 "
C_2S " - 19.0 to 55.8 "
Fineness ranged from 1385 to 2340 sq. cm. per g., turbidimeter method.

It is interesting to note from Andrews' paper that, with this rather wide range in composition and fineness there were few instances where non-air-entraining cements produced concrete pavements that were free from surface scaling or D-cracking. On the other hand, the pavements constructed with air-entraining cements, covering about the same range in composition and fineness, showed no evidence of surface scaling or D-cracking after 10 to 14 years of service.

Three different air-entraining agents, Vinsol resin, tallow, and fish oil were interground with the clinker in the preparation of the air-entraining cements used on the experimental projects. It is of interest to note that all three of these air-entraining agents provided the same superior resistance to surface scaling and D-cracking.

The results obtained from these experimental projects indicate that the use of any one particular ASTM type of portland cement, or other special limitations in chemical composition of fineness, has not improved the resistance to surface scaling or D-cracking of these projects. Air-entrainment is the answer. Jackson[1] and Jackson and Tyler[2] reached the same conclusion on the basis of the performance of the New York Test Road of the Long-Time Study of Cement Performance in Concreté. In the latter paper the authors concluded that: "The effects of air-entrainment on improving the resistance of the pavement to scaling and weathering overshadow all other variables."

L. E. ANDREWS, Closure - The analyses of the cements used in the test roads as reported by William Lerch with respect to type and chemical composition provide an important addition to the paper.

The conclusion reached by F. H. Jackson and I. L. Tyler on the Long-Time-Study Test Road in New York, as referred to by Lerch, is truly significant of experience throughout the country.

It developed that cement type and degree of fineness without air entrainment were not factors in securing resistance to scaling and D-cracking. On the other hand, as emphasized by Lerch, the use of air entrainment, irrespective of cement type, fineness, or chemical composition, produced concrete which has been highly resistant to scaling and D-cracking everywhere.

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[1] F. H. Jackson, "Why Type II Cement," Proceedings Am. Soc. for Testing Mat., v 50, p. 1210 (1950).

[2] F. H. Jackson and I. L. Tyler, "Long-Time Study of Cement Performance in Concrete - Chapter 7, New York Test Road," Proceedings Am. Concrete Inst., v. 47, p 773 (1951).

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