FINAL REPORT

AIR VOID CHARACTERISTICS OF HARDENED CONCRETE 1945-1980

by

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ABSTRACT

Observations at the Research Council, coupled with the national interest in possible changes in the air void characteristics of air-entrained concretes because of the wide use of admixtures and changes in cement properties, raised a question as to whether or not there was a progressive increase over the years in the size of air voids being incorporated in concrete. Thus, the main objective of the study reported here was to evaluate the changes in air void characteristics of hardened concrete as determined by ASTM C457 and by other means for concrete produced in Virginia from 1945 to 1980. Air void parameters -- including the air content, specific surface, and spacing factor -- were determined on 630 concretes. The results did not indicate an overall significant increase in the size of air voids; however, it was observed that, in general, they did show that the average size and the distribution of the voids were marginal compared to generally accepted values. While this finding indicates that air voids may not be as small as optimum, the freeze-thaw performance of air-entrained concretes in Virginia supplied under the present specifications generally has been satisfactory.

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INTRODUCTION

Air entrainment, one of the most significant developments in concrete technology in the twentieth century, makes portland cement concrete resistant to damage from cycles of freezing and thawing. For approximately 40 years the benefits of air entrainment have been demonstrated repeatedly in both the laboratory and the field.

The total content, size, and spacing of the air voids are important. Powers originated the concept of a void spacing factor that indicates the average distance water must travel to reach a protective air void in concrete undergoing freezing.(1) The spacing factor, $\bar{L}$, is a calculated parameter that involves the ratio of paste to air content and the size of the air bubbles. Thus, changes in any of these components will result in a change in $\bar{L}$. He estimated the maximum allowable spacing factor necessary for adequate resistance to damage from freezing and thawing to be 0.01 in. Subsequently, Mielenz et al. suggested a maximum effective spacing factor of 0.004 in to 0.008 in.(2) In summarizing studies prior to 1966, Klieger stated that an upper limit of 0.006 in to 0.008 in is required for extreme exposures.(3) Since that time the value of 0.008 in generally has been accepted. In addition, other methods of determining spacing factors have been proposed,(4,5) including extending the concept to three dimensions.(6) Powers initially stated that the specific surface, α, of air void systems in concrete, including both entrained and entrapped air voids, may be as low as 300 and as high as 800 in^{-1}.(7) Mielenz and his coworkers stated that α values may be expected to range from 600 to 1,100 in^{-1}.(2) Based upon these various studies, it generally has been agreed that for adequate protection the volume of air in the mortar fraction should be no less than about 9%,(3) the specific surface should be greater than approximately 600 in^{-1}, and the spacing factor should be less than 0.008 in.

Subsequent to the establishment of criteria for α and $\bar{L}$, the widespread increase in the use of chemical admixtures and changes in cement properties have raised questions as to the validity of the initial criteria as applied to present concretes. This concern was the subject of a discussion at a meeting of the American Concrete Institute in March 1980,(8) where the possibility of significant changes in the air void system having occurred was discussed but no supporting data were available.

At the Research Council, the air void system in hardened concrete has been determined by the linear traverse method for about 20 years by the procedure stated in ASTM Recommended Practice C457, Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete. The data from these determinations have been collected in connection with a variety of field and laboratory research projects as well as studies of field concretes that have exhibited unusual performance. These data, along with other information taken on field concretes placed in the late 1940's, were believed to offer an opportunity for examining changes in air void systems that might have occurred during a 35-year period.

OBJECTIVE

The objectives of this project were --

1. to evaluate the changes in air void characteristics of hardened concrete as determined by ASTM Method C457 for concrete produced in Virginia from 1945 to 1980, and

2. to correlate the observed changes, if any, with changes in materials and practices used in concrete production.

PROCEDURE

The linear traverse data accumulated at the Council over the years were gathered, and a preliminary evaluation was made to select data for which complete information for the air void characteristics was available. In addition, in order to cover the longest possible time period, concrete samples from early projects in Virginia were collected and tested for the air void characteristics and all of the data were combined for analysis. Overa_l, 630 samples representative of the different classes of concrete placed between 1945 and 1980 were available.

For all samples the chord lengths, which had been recorded on paper tape, were transferred to computer cards for the calculation of the air void characteristics. The air void parameters determined are summarized in Table 1. In addition to the standard parameters mentioned in ASTM C457 others, such as the spacing factors obtained with the Sommer(4) and Walker(5) methods, the Philleo factor(6), the void (bubble) diameters and the number of voids (bubbles) per unit volume by the Lord and Willis method,(9) are included.

TABLE 1
Air Void Parameters

1. Diameter of the bubble by Lord and Willis
2. Specific surface by Lord and Willis
3. Number of voids (bubbles) by Lord and Willis
4. Specific surface for total voids by ASTM C457
5. Specific surface for small voids by ASTM C457
6. Average chord lengths
7. Median chord interval
8. Total void content
9. Void content for small voids
10. Void content for large voids
11. Percent small voids per total void content
12. Percent large voids per total void content
13. Total number of voids per length of traverse
14. Number of small voids per length of traverse
15. Number of small voids per total number of voids
16. Average chord length of 3 maximum consecutive chord intervals
17. Spacing factor by the long equation in ASTM C457
18. Spacing factor by Sommer
19. Spacing factor by Walker
20. Spacing factor by the short equation in ASTM C457
21. Spacing factor by ASTM C457
22. Philleo factor

The standard specific surface, and spacing factor are given in ASTM C457 as

$$\alpha = 4/\bar{\ell}$$

$$\bar{L} = p/A\alpha \qquad \text{when } p/A < 4.342\text{, and}$$

$$\bar{L} = (3/\alpha)[1.4((p/A)+1)^{1/3}-1] \qquad \text{when } p/A > 4.342,$$

where

$\bar{\ell}$ = average chord intercept,

p = paste content in volume percent of concrete, and

A = air void content, in percent.

The above formulas used by ASTM were derived by Powers.(1)

Sommer used the spacing factor formula given in ASTM C457, but utilized only the small spherical voids rather than the total voids. Walker derived a spacing factor for only small voids from the proportion of small voids to total voids.

The Philleo factor is the distance from the perimeter of the nearest void in which most of the paste (usually 90% as used in this study) is protected from the effects of freezing. It is based on the total air content in the paste and the number of voids per unit volume of the paste. The latter parameter is obtained using a graphical method presented by Lord and Willis.(9) In their method, chord lengths obtained by linear traverse analysis are classified into discrete small groups to generate a chord frequency distribution curve. The distribution curve is used to determine the number of air voids per unit volume of concrete, which is then converted to paste volume.

CHARACTERISTICS OF THE DATA

The vast majority of the data used in the study were accumulated in lab or field work done for a variety of reasons over a period of time prior to the initiation of the project. Therefore, a completely balanced representation of age and class of concrete, materials, and type of construction was not possible. During the period over which the data were accumulated, three significant changes in the air content requirements were made as shown in Table 2. The data distribution for four time periods between 1945 and 1980 is shown in Table 3 along with the class of concrete and the place of production, i.e., laboratory or

TABLE 2
Concrete Requirements

	Time Period					
	1945-55		1956-65		1966-80	
Class of Concrete	Paving	Bridge Deck	P(AE) Paving	A(AE) Bridge	A3 General Use and Paving	A4 Bridge
W/C Ratio	0.53	0.53	0.49	0.49	0.49	0.47
Strength, psi	3,000	3,000	3,000	3,000	3,000	4,000
Air, percent	*	*	3-6	3-6	6 ± 2	6½ ± 1½

* Project-by-project basis.

TABLE 3
Number of Samples

	Lab				Field				Lab & Field			
Time Period	A3	A4	M	T	A3	A4	M	T	A3	A4	M	T
1945-55	-	-	-	-	16	11	-	27	16	11	-	27
1956-65	-	-	-	-	-	111	-	111	-	111	-	111
1966-75	21	-	7	28	33	68	15	116	54	68	22	144
1976-80	22	138	39	199	38	76	35	149	60	214	74	348

field. The time periods were chosen to reveal trends in the air void system over the years and to reflect changes in the air content requirements in the specifications. The first time period included early projects that incorporated the first air-entrained pavement in Virginia, which was built on Rte. 460 at Waverly in 1946 using type II-A and type II cements, and the first major air-entrained pavement in the state, which was built on Rte. 350 (the Shirley Highway) in Fairfax County in 1950-51 using type I and type II cements with an air-entraining admixture. Also included was the first bridge containing air entrainment, the Westham or Huguenot Bridge built on Rte. 147 in 1949 using type II cement and an air-entraining admixture. The second period included data from a study of bridge decks which evaluated the performance of 17 decks through observations and sampling.(10) The third and fourth periods reflect primarily bridge deck concrete, prepared in the field or the laboratory, that includes general use, paving, and miscellaneous concrete. The classes of concrete are given as A3, A4, M, and T in Table 3. A3 and A4 are the designations put into the Department's specifications in 1966,(11) which included the revisions of air content requirements introduced in 1965. A3 is used for general use and paving and A4 for bridge decks. At earlier times different designations were used and different requirements were specified as shown in Table 2. However, in this report the A3 and A4 designations were used for all periods to distinguish the paving or general use concrete from the bridge deck concrete, even though different requirements were enforced at different times. It is important to note that in the period from 1966 to 1980 concretes had a significantly higher air content requirement, 1.5% to 2.0% more for the average values, compared to the earlier period. M in Table 3 stands for miscellaneous and includes concretes other than the regular A3 and A4 mixtures, such as the patching materials, latex modified concrete, and concretes with high-range-water reducers and hollow plastic microspheres. The miscellaneous concretes generally have air void system requirements different from those for the regular A3 and A4 concretes. T designates total and includes A3, A4, and M mixtures.

It is also important to note that the data include some concretes prepared for laboratory and field research projects, or field troubleshooting projects, that either intentionally or inadvertently did not meet the specifications.

RESULTS

Standard ASTM Practice

The microscopical determinations of air void contents, specific surface, and spacing factors were made using the linear traverse method described in ASTM C457.

Air Void Contents

The average total air void contents are summarized in Table 4. The averages of the small voids less than 1mm in diameter are given in Table 5, and the averages of the larger ones are given in Table 6. In these tables the values are given for A3 and A4, and lab and field concretes separately and combined.

TABLE 4
Total Air Contents, in Percent

Time Period	A3	A4	A3	A4	A3	A4	M	Total
1945-55	-	-	4.2	6.3	4.2	6.3	-	5.0
1956-55	-	-	-	6.5	-	6.5	-	6.5
1966-75	6.8	-	7.0	8.2	6.9	8.2	6.8	7.5
1976-80	5.9	6.4	6.8	8.4	6.5	7.1	7.4	7.1

TABLE 5
Air Voids <1mm, in Percent

	Lab		Field		Lab & Field			
Time Period	A3	A4	A3	A4	A3	A4	M	Total
1945-55	-	-	2.7	4.5	2.7	4.5	-	3.4
1956-65	-	-	-	4.0	-	4.0	-	4.0
1966-75	5.9	-	4.8	6.2	5.2	6.2	4.7	5.6
1976-80	4.2	4.3	4.9	6.2	4.6	5.0	4.3	4.8

TABLE 6
Air Voids >1mm, in Percent

	Lab		Field		Lab & Field			
Time Period	A3	A4	A3	A4	A3	A4	M	Total
1945-55	-	-	1.5	1.8	1.5	1.8	-	1.6
1956-65	-	-	-	2.5	-	2.5	-	2.5
1966-75	0.9	-	2.2	2.0	1.7	2.0	2.1	1.9
1976-80	1.7	2.1	1.9	2.2	1.9	2.1	3.1	2.3

The combined lab and field data included values for M, the miscellaneous concretes. The results indicate that concretes prepared for the period after 1966 had a higher void content as well as more small voids than concretes of the earlier period, which would be expected because of the changed air void content requirements. The increase in void content requirements was about 2% for concrete used in bridge decks and is reflected very closely in the field data. The A4 bridge deck concretes from the field had average total void contents exceeding the upper specification limits in all periods, which reflects the fact that many times bridge deck concretes are sent to the Research Council to be examined for lower than anticipated strengths and that these low strengths are due to excessive amounts of air, usually above 10%. The large air voids averaged about 2% throughout the periods covered. This conforms with information from past Council work and assumptions in ACI 211, Recommended Practice for Selecting Proportions for Normal and Heavyweight Concrete, which indicates an approximate amount of entrapped air in non-air-entrained concrete to be 2.0% for a nominal maximum aggregate size of 3/4 in.

Specific Surface

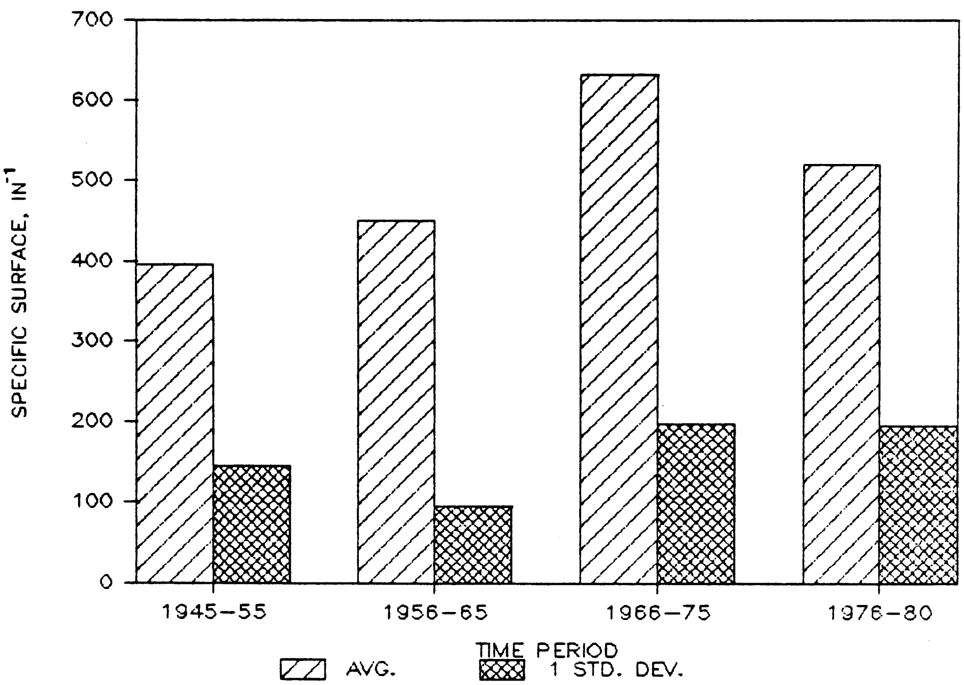
The averages of the specific surfaces obtained by ASTM C457 are given in Table 7. Also the average and the standard deviation of the total data are shown graphically in Figure 1.

The data in Table 7 show that values for the two last periods are somewhat larger than those for the two early periods, an indication that if any changes have occurred, the bubbles have gotten smaller. However, the data do not support a continuing trend since 1966. For example, the laboratory A3 concretes show specific surface values of 852 in^{-1} in the third period and 597 in^{-1} in the fourth period. Similarly, the A4 field concretes had specific surfaces of 662 $in.^{-1}$ and 598 in^{-1} for the third and fourth periods, respectively. The implications from these average values are that after a significant increase in the specific surface values, probably attributable to the change in specifications, there was a decrease in value and this was probably a result of an increase in the bubble size during the 1976-80 period. However, the standard deviation values were high, being 128 in^{-1} and 271 in^{-1} for the former A3 concretes and 167 in^{-1} and 180 in^{-1} for the latter A4 concretes, respectively. Considered along with the standard deviation values shown graphically in Figure 1 for the total data, these values indicate high variabilities, which fact creates uncertainties as to the significance of the noted changes in the average specific surface

Table 7
Average Specific Surface by ASTM C457, in^{-1}

Time Period	Lab		Field		Lab & Field			
	A3	A4	A3	A4	A3	A4	M	Total
1945-55	-	-	335	485	335	485	-	396
1956-65	-	-	-	451	-	451	-	451
1966-75	852	-	522	662	650	662	496	632
1976-80	597	481	504	598	538	522	501	521

FIG. 1. SPECIFIC SURFACE – ASTM



values. The specific surface values are a good indication of the size of bubbles in concrete, and this parameter would be expected to increase with void content. The extent of increase in α with an increase in void content depends upon the proportion of small voids, because α is based on the average chord intercept of the voids, which gets smaller as the ratio of small voids to larger ones increases, as was the case in the present study. Consequently, a large amount of small air voids in the recent concretes could have caused the high α values. Thus, the increase in specific surface observed after the specification changes does not appear to indicate significant changes in bubble size.

The changes between the third and fourth periods are somewhat reflected in the large bubbles found in the recent concretes. However, the large variabilities obtained make it difficult to conclude that any significant changes have occurred.

It is noted that the α values obtained were close to or lower than the low limit stated by Mielenz et al., but more in agreement with that advocated by Powers.

To gain further insight into changes in the bubble size, a study of the specific surface of only the small voids was attempted. The bubbles stabilized in concrete through air entrainment are small, and considering them apart from the coarser bubbles, which are generally related to the level of consolidation or high water-cement ratios, would better describe the average size of beneficial bubbles. Specific surface values of the small bubbles were obtained using the formula given in ASTM C457, and the average values with the corresponding standard deviations are summarized in Table 8. The results were similar to the ones obtained when the total air voids were considered. The standard deviations were very large; in some cases even larger than the average values, which makes any conclusions questionable. The large variabilities are due to the wide range of air contents exceeding the specification limits found in the field concretes. For example, for the 1966-1975 time period , the range for the A4 field concretes was from 3.6% to 12.9%. Similarly, the A4 laboratory concretes showed large variabilities because a wide range of air contents was intentionally incorporated.

TABLE 8
Specific Surface Data for Voids <1mm using ASTM C457, in^{-1}

Standard Deviation Values are shown in Parentheses Below the Averages

Time Period	Lab A3	Lab A4	Field A3	Field A4	Lab & Field A3	Lab & Field A4	Lab & Field M	Total
1945-55	-	-	526 (97)	652 (108)	526 (97)	652 (108)	-	577 (118)
1956-65	-	-	-	684 (494)	-	684 (494)	-	684 (494)
1966-75	972 (139)	-	729 (156)	1,065 (1,215)	824 (191)	1,065 (1,215)	729 (253)	923 (857)
1976-80	803 (365)	816 (1,714)	726 (218)	802 (230)	754 (280)	811 (1,381)	817 (802)	802 (1149)

Spacing Factor

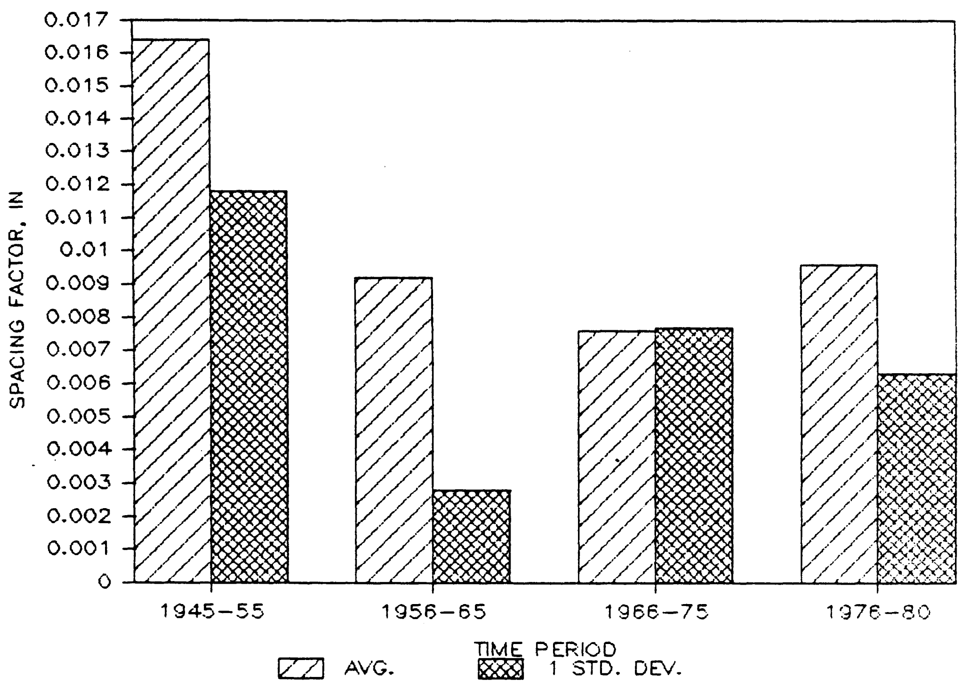
The averages of the spacing factors obtained by ASTM C457 are shown in Table 9. Also, the average and the standard deviation for the total data are shown graphically in Figure 2.

The data in Table 9 for bridge deck concretes prepared in the field indicate a decrease in the values after 1966, which would be expected because of an increase in void contents. However, when the total data are considered, as illustrated graphically in Figure 2, this decrease is not evident, since the values for the second period when the low air content requirement was in effect are similar to those for the last period when

TABLE 9
Spacing Factors by ASTM C457, in

Time Period	Lab A3	Lab A4	Field A3	Field A4	Lab & Field A3	Lab & Field A4	Lab & Field M	Total
1945-55	-	-	0.0213	0.0091	0.0213	0.0091	-	0.0164
1956-65	-	-	-	0.0092	-	0.0092	-	0.0092
1966-75	0.0047	-	0.0095	0.0059	0.0076	0.0059	0.0128	0.0076
1976-80	0.0093	0.0096	0.0116	0.0065	0.0107	0.0085	0.0120	0.0096

FIG. 2. SPACING FACTOR – ASTM



high air contents were required. The difficulty could result from the large variation in the spacing factors seen in Figure 2. The $\bar{L}$ values for the third and fourth periods indicate an increase in spacing between bubbles that is consistent with the α values. Equal amounts of coarse bubbles would be farther from each other than the small ones. However, again the large variabilities hinder firm conclusions.

The $\bar{L}$ data indicate that the average values are generally marginal or outside the range recommended by Mielenz et al., but more in agreement with the limits originally proposed by Powers.

Other Parameters

The other parameters summarized in Table 1 also indicate that significant changes in bubble size have not occurred over the years. For example, in Figure 3 the mean sphere diameters obtained by the Lord and Willis method for the four time periods are shown along with thestandard deviations. The average for the first period was lower than those for the last two, while that for the second period was higher. The standard deviations were high. A significant change in diameter cannot be confirmed.

Figure 4 shows the number of bubbles in a unit volume of concrete as calculated by the Lord and Willis method. The values indicate the increase in the number of bubbles as expected because of increases in the air content. Spacing factors for the total data found by the Sommer and Walker methods, given in Figures 5 and 6, exhibit results similar to those obtained by ASTM C457 and shown in Figure 2. Figure 7 shows that use of the Philleo factor gave somewhat similar results. The wide variability in values makes it difficult to draw firm conclusions.

FIG. 3. MEAN SPH. DIA.— LORD & WILLIS

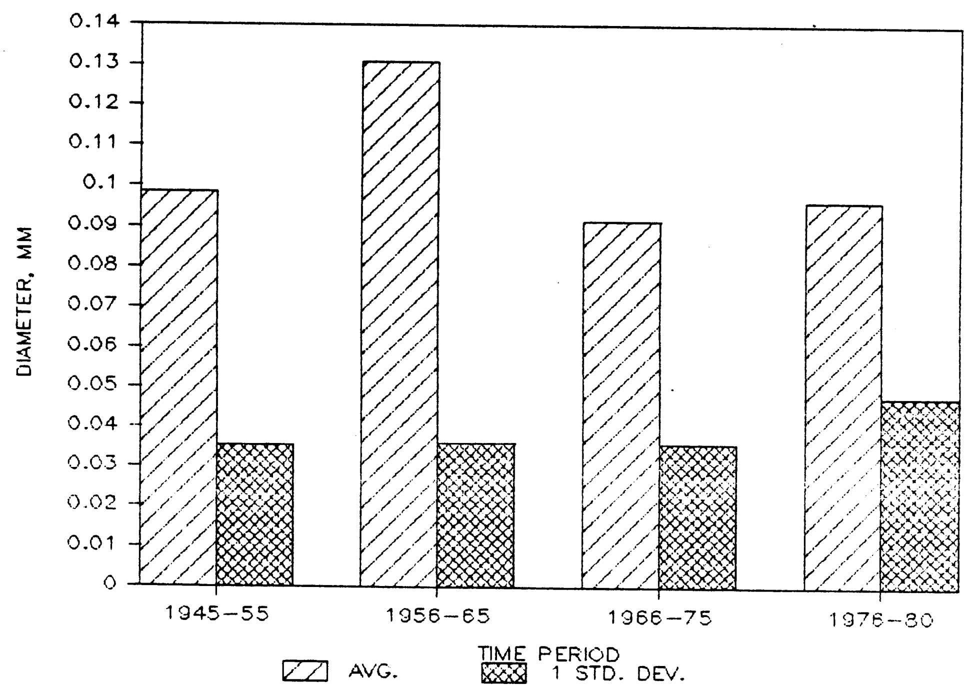


FIG. 4. NUMBER OF SPHERES

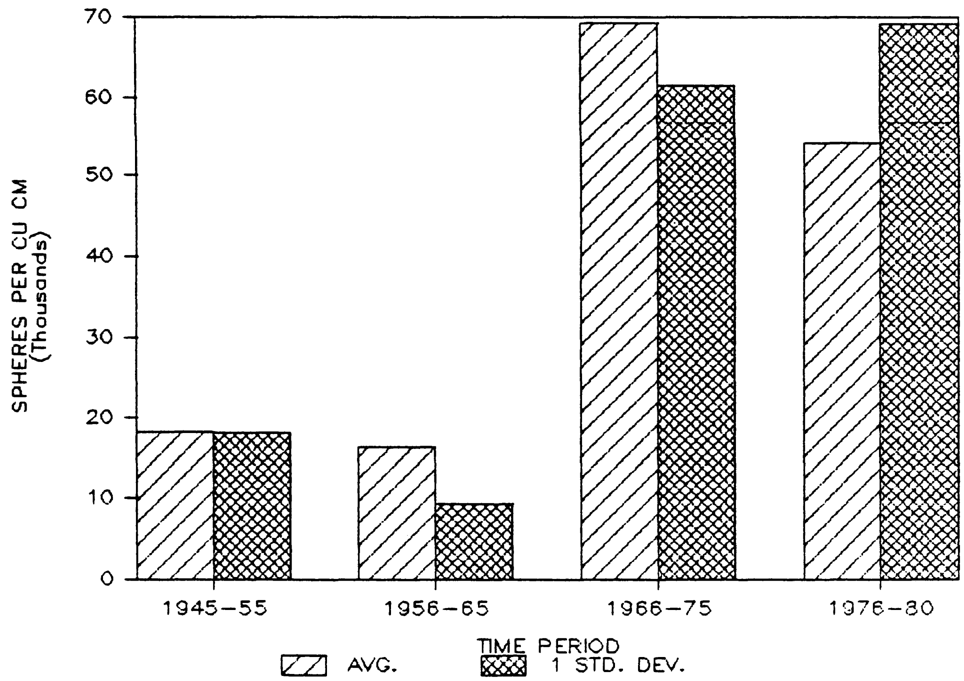


FIG. 5. SPACING FACTOR — SOMMER

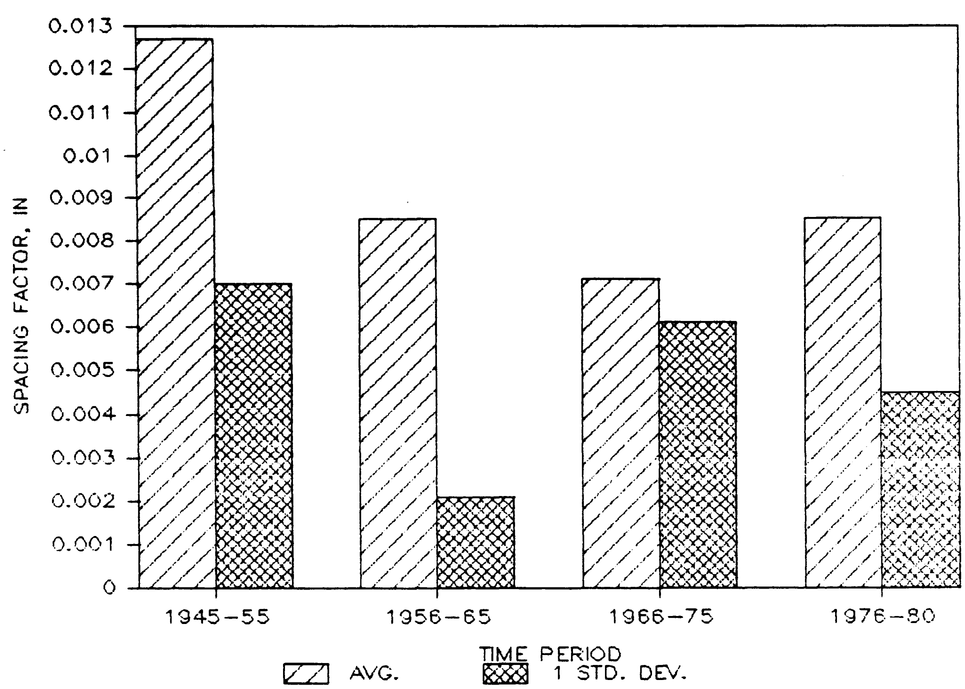


FIG. 6. SPACING FACTOR — WALKER

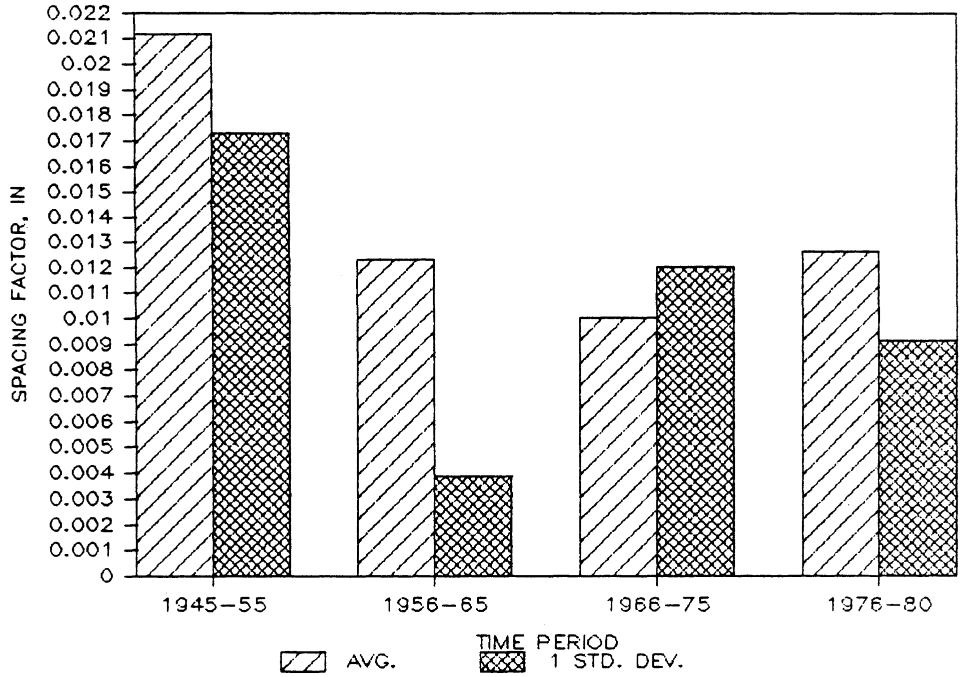
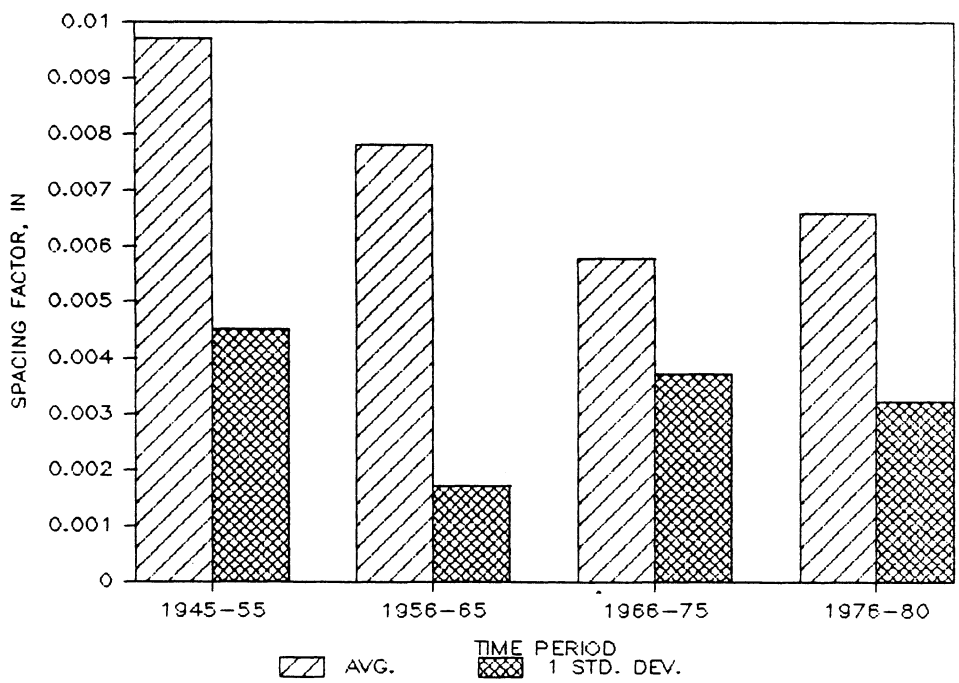


FIG. 7. PHILLEO FACTOR



FINDINGS AND CONCLUSIONS

The following findings and conclusions are drawn from data accumulated from a variety of laboratory and field air-entrained concretes which included specially designed and non-specification mixtures. The data, obtained over the years between 1945 and 1980, were divided into four time periods. For the last two, between 1966 and 1980, the specifications required an increased air content.

1. The overall average of total air void contents increased about 2% after 1966, which reflects the change in the specifications that increased the required air content by about 2%.

2. The study did not reveal any significant trends towards an increase in the size of bubbles in air-entrained concretes over the years considered.

3. The amounts of large air voids averaged around 2% throughout the period covered, which is consistent with ACI 211 assumptions.

4. The specific surface values showed some increase and then a decline after 1966.

5. As shown by the bridge deck concretes prepared in the field, the spacing factor values were smaller after 1966, which would be expected because of an increase in void contents. For the 1976-80 period, spacing factors were higher than for the preceding period, which indicates a farther separation of the bubbles. However, the large standard deviations prevent the drawing of firm conclusions.

6. The specific surface and spacing factor data indicate that the average values are generally marginal or outside the range recommended by Mielenz et al. Even though this is the case, the freeze-thaw performance of air-entrained concretes prepared in the laboratory or supplied under the specifications in effect since 1965 generally have been satisfactory. It should be noted that the various values obtained are more consistent with the limits originally proposed by Powers.

7. Since suspected changes in the air void characteristics could not be confirmed with the available data, the second objective of the study could not be addressed.

RECOMMENDATION

At present, it should be assumed that significant changes in the air void characteristics have not occurred over the years. However, continuing wide use of admixtures, changes in admixtures, and changes in cement properties could result in such changes in the future. The collection of data should be continued, and further evaluations of possible changes in air void characteristics should be made periodically.

ACKNOWLEDGEMENTS

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