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Special Report 47

Report on Cooperative Freezing-and-Thawing Tests of Concrete

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Report on Cooperative Freezing-and-Thawing Tests of Concrete

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Preface

The Highway Research Board Committee on Durability of Concrete—Physical Aspects, began in 1947 to consider the need for setting up a committee to conduct a new cooperative program of freezing-and-thawing tests. The minutes of the committee for December 3-4 of that year state: "The objective of the committee was defined as the development of a procedure for conducting a rapid but highly discriminating freezing-and-thawing test for concrete."

Before the program was launched, however, the ASTM published four tentative methods of test for resistance of concrete specimens to freezing and thawing. It was decided, therefore, that instead of following the previously stated object of developing a procedure, a cooperative program should be carried out using and evaluating these four methods. The minutes of January 14, 1952, state: ". . . it was agreed that a (planning) committee should give careful study to the proposed 1947 program and present . . . a proposal for a new program on durability of concrete. The committee is: William Lerch, Chairman; A. G. Timms, T. F. Willis, Bryant Mather." Drafts were prepared, distributed, and discussed, both by correspondence and at the meeting of January 12-13, 1953. The program outline dated August 5, 1953, was accepted and the planning committee discharged at the meeting of January 11, 1954. The outline includes the following statement: "The final objective is to develop a reproducible, accelerated laboratory freezing-and-thawing test that will differentiate between concretes of varying degrees of durability in a manner similar to that exhibited by the same concretes in service under actual weathering . . . . The purpose of this proposed program is to determine the reproducibility of results that can be obtained, within one laboratory and between different laboratories, by the different ASTM methods." Upon acceptance of the planning committee report, an Operating Committee was appointed as follows: B. E. Foster, Chairman, National Bureau of Standards; D. L. Bloem, National Sand and Gravel—National Ready-Mixed Concrete Association; R. E. Bollen, Nebraska State Highway Department; G. H. Larson, Wisconsin State Highway Department; D. W. Lewis, Purdue University; R. R. Litehiser, Ohio State Highway Department; Bryant Mather, U. S. Army Engineers Waterways Experiment Station; Bert Myers, Iowa State Highway Department; A. G. Timms,

U. S. Bureau of Public Roads; M. O. Withey, University of Wisconsin; and Hubert Woods, Portland Cement Association. Additional members were appointed to the Operating Committee, as needed, so that each cooperating laboratory was represented; these were J. E. Backstrom, U. S. Bureau of Reclamation; J. F. McLaughlin, Purdue University; J. M. Rice, National Crushed Stone Association; W. M. Carver, Nebraska State Highway Department; V. R. Sturrup, Hydro-Electric Power Commission of Ontario; Paul Klieger, Portland Cement Association; J. B. Blackburn, Purdue University; George Werner, U. S. Bureau of Public Roads. A committee to analyze the results and prepare the report was appointed as follows: B. E. Foster, Chairman; J. B. Blackburn, D. L. Bloem, J. F. Backstrom, Paul Klieger, William Lerch, Bryant Mather, Howard Arni.

The work described in this report has been made possible by the generous support in time and expense of a number of organizations and individuals. The laboratories which participated in the freezing-and-thawing tests and the individuals representing each have been listed previously.

A test program of this size, involving concretes and the use of aggregates and cement from single lots, presented formidable supply problems. Materials were furnished as follows:

The limestone was crushed, freed from fines, and delivered to the Iowa State Highway Commission Laboratory through the courtesy of B. L. Anderson, of B. L. Anderson, Inc., Rapid City, Iowa. It was blended for uniformity, separated into sizes, and bagged for shipment by Bert Myers and his laboratory staff at the Iowa State Highway Laboratory, Ames, Iowa.

The National Sand and Gravel Association, Washington, D. C., separated the gravel into size fractions and bagged it for shipment.

The Concrete Division of the U. S. Army Engineers Waterways Experiment Station, Jackson, Miss., separated the sand into size fractions, re-combined it in the specified proportions, and packaged it in metal containers for shipment.

The Portland Cement Association, Skokie, Ill., furnished the cement, packed in steel containers.

The National Bureau of Standards furnished the calibrated steel bars used for checking calibration stability of the sonic apparatus in the different laboratories.

Membership of the operating committee which conducted the tests and of the committee which analyzed the data and prepared the report has been listed previously.

Particular acknowledgment is due to Howard Arni, who not only prepared the general sections on concrete data, performance of apparatus, freezing-and-thawing data, and statistical analysis of the results, but also brought all the sections together into the finished report.

The methods employed in the statistical treatment of the data were suggested by W. S. Connor of the Statistical Engineering Laboratory, National Bureau of Standards, and his continued interest and assistance in this phase of the work were invaluable.

Finnally, acknowledgment should be made to the many technical and supporting personnel in the various participating laboratories, without whose careful effort this project could not have been successfully carried out.

Contents

Report on Cooperative Freezing-and-Thawing Tests of Concrete

A program of cooperative freezing-and-thawing tests of concrete specimens was conducted by thirteen laboratories using the four ASTM Tentative Methods of Test. Three concrete mixtures were used, involving different aggregates and two different air contents. Large variations in durability were found for the same concrete mixture and for tests by the same method, both within and between laboratories. It is indicated that these were due both to differences in the concretes as prepared in the laboratories and in treatment of the specimens by a given test method. Differences in specimens consisted mainly in unexpectedly large variations in air content and air-void characteristics revealed by microscope measurements of the air-void systems in some of the test specimens. Differences in the treatments were greatest in the methods involving freezing in air, and were probably due in part to unequal amounts of drying during freezing. A statistical examination of the data and a comparison with previous programs are presented. It is concluded that these methods provide useful procedures for comparing the relative durability of different concretes within a given laboratory; that a wide variation of results in the middle range of durability appears to be a normal characteristic of the methods; that the data do not permit recommending one test method over the others for all purposes; and that the ability of concrete to withstand a severe laboratory freezing-and-thawing test is probable indication of a high degree of durability.

● IT HAS BEEN RECOGNIZED for many years that concrete which is saturated or nearly saturated with water may deteriorate when subjected to alternate cycles of freezing and thawing. Since the presentation by Scholer (1) of the first paper describing laboratory freezing-and-thawing tests of concrete, many papers have been written on this subject. In the early stages of the art, each laboratory designed its own freezing equipment and developed its own preliminary curing procedure and method of test. As the studies progressed, efforts were made to standardize the equipment and procedure. These various studies have been summarized in an annotated bibliography (2).

The Highway Research Board Committee on Durability of Concrete—Physical Aspects conducted and reported two previous series of cooperative freezing-and-thawing tests designed to study factors that influence resistance of concrete to freezing and thawing and to develop a standardized method of test. The first of these series of tests, reported in 1936 (3), used mortar prisms made with ten commercial portland cements differing in chemical composition. The second series of tests, reported in 1944 (4), used concrete specimens.

The information obtained from these two series of tests and from reports from other laboratories emphasized the necessity for carefully regulating the methods of making and curing the specimens, the air content of the specimens, the degree of saturation of the aggregate at the time of mixing the concrete, and the degree of saturation of the concrete at the time of freezing.

As studies of freezing-and-thawing tests progressed, Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials prepared four Tentative Methods of Test for Resistance of Concrete Specimens to Freezing and Thawing, ASTM Designations C 290-52T, C 291-52T, C 292-52T, and C 310-53T (5). These methods of test embodied the essential features of the test procedures employed in different laboratories.

The Highway Research Board Committee on Durability of Concrete—Physical Aspects approved a new program of cooperative freezing-and-thawing tests at its meeting on

January 11, 1954. The preparation of the program of tests took advantage of experience obtained by the two previous programs, subsequent experience of different laboratories, and the ASTM Methods of Test.

This report reviews briefly the two prior test programs and describes the procedures used and the results obtained from the cooperative freezing-and-thawing test program authorized in 1954.

REVIEW OF PREVIOUS PROGRAMS

The object of the program reported in 1936 (3) was to ascertain the relative resistance to freezing and thawing, and to certain other influences, of several commercial portland cements differing in composition. The principal tests consisted of flexure and compression tests on mortar prisms containing one part cement to two parts of fine aggregate by weight after they had been subjected to 100 or more cycles of freezing and thawing. The procedures used for the freezing-and-thawing tests were the procedures then in use by the various participating laboratories. No attempt was made to use a standardized test procedure.

The significant effect of the air content of mortars and concretes on their resistance to freezing and thawing was not recognized at the time this program was conducted. No tests were made to determine the air content of the mortars. It was observed that there was a significant difference in resistance to freezing and thawing of the mortars made with the different cements, but there was no clearly defined relationship between resistance to freezing and thawing and the chemical composition of the cement. On the basis of present knowledge it appears probable that the observed difference in resistance to freezing and thawing could be accounted for, at least in part, by differences in the air contents of the mortars. It is now known that even with non-air-entraining cements varying quantities of air are entrained in mortars and concretes.

The program reported in 1944 (4) consisted of freezing-and-thawing tests of concretes and involved the following:

1. A comparison of the relative severity of a carefully specified coordinating freezing-and-thawing test, as performed in different laboratories.
2. A comparison of the effects of freezing-and-thawing procedures commonly used in these laboratories (local procedures).
3. A comparison of the severity of the coordinating test procedure with the local laboratory procedures.

The coordinating freezing-and-thawing test consisted of freezing in air and thawing in water. Several different methods of test were used to evaluate the resistance of the concrete to freezing and thawing.

The most significant conclusions from this test program were as follows:

1. Under the conditions of these tests the electronic vibrating devices used provided a convenient and rapid means of determining the change in the dynamic modulus of elasticity of the specimens tested.
2. The local test procedures having the fastest rates of freezing and producing the quickest failures did not discriminate clearly between the concretes made with satisfactory and those made with poor coarse aggregates, whereas the procedures in which the rates were somewhat slower and the number of cycles to failure greater provided good discrimination.
3. None of the freezing-and-thawing procedures tried provided a small dispersion in the number of cycles required for failure and a sufficiently high degree of discrimination to qualify as a standard method. With still better control of the variables it was believed that these dispersions could be reduced and a standard procedure established.
4. The data emphasized the necessity for careful regulation of the methods of making and curing the specimens, the air content of the specimens, the degree of saturation of the aggregate at the time of making, and the degree of saturation of the concrete at the time of freezing.

OUTLINE OF 1959 PROGRAM

Three concretes selected to represent good and poor frost resistance were used in the test program. The methods for soaking the aggregates in water, making and curing the test specimens, and controlling the degree of saturation of the concrete at the time of freezing, were described in detail. An effort was made to control the air content of the concrete within definite narrow limits. Some specimens were set aside for determination of air content of the hardened concrete, as a means of interpreting variations in results that might be obtained by different laboratories. Each participating laboratory was to use, and follow as closely as possible, one or more of the ASTM tentative methods of test for freezing and thawing concrete specimens.

Materials Used

Aggregates. One fine aggregate of good quality was used in all three concretes. Two concretes having different air contents were made with a gravel coarse aggregate of good uniform quality. A limestone coarse aggregate having a relatively poor service record was used with entrained air in the preparation of the third concrete.

The coarse aggregates were separated into three sizes, the fine aggregate into five sizes, then recombined in the following gradings:

Aggregate	Retained on Sieve (percent)									
	1 In.	3/4 In.	1/2 In.	3/8 In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100
Coarse	0	20	50	75	100					
Fine	-	-	-	-	0	18	33	57	80	95

Cement. The same Type I cement was used by all participating laboratories.

Air-Entraining Admixture. A neutralized Vinsol resin solution was used as the air-entraining admixture by all participating laboratories. The laboratory that established the concrete-mixture proportions provided the participating laboratories with a solution of the same concentration as that used in the mixture-proportioning work.

Saturation of Aggregates

To avoid the effects of variations in the amount of absorbed water in the aggregates, the laboratories were instructed to treat the aggregates as follows: Dry the coarse aggregates on the laboratory floor for two days and then store them in closed metal containers. Make a moisture determination on a weighed sample of each aggregate. Make 7-day absorption determinations of the dried aggregates by the procedures described in ASTM C 127-42 and C 128-45 (5). Seven days prior to mixing, combine the proper amounts of each size fraction for each batch to be mixed, and place the aggregate for each batch in a closed metal container. Inundate each batch with a weighed amount of water, leaving the batches in this condition until just before mixing the concrete.

Proportioning of Concrete Mixtures

One laboratory selected proportions for the concrete mixtures, and the proportions furnished were used by all participating laboratories, except that each laboratory varied the amount of air-entraining admixture to obtain the prescribed amount of air. The concrete mixtures were proportioned to have a cement content of 5.5 ± 0.1 bags of cement per cubic yard and a slump of 2 to 3 in. The three concretes and their designations were:

LG - Good quality coarse aggregate concrete, 2½ to 3 percent air.
HG - Good quality coarse aggregate concrete, 6 to 7 percent air.
HP - Poor quality coarse aggregate concrete, 6 to 7 percent air.

Mixing the Concrete

All materials and equipment used in the tests were required to be stored in the mixing room for at least 24 hr prior to use. The temperature and humidity of the mixing room at the time of mixing the concretes were determined and reported.

The procedure for mixing the batches was specified as follows: Place the aggregates and water in the mixer and start the mixer; add the cement and continue mixing for two minutes; allow the batch to rest for three minutes and then remix for one minute; dump the contents of the mixer into a moistened metal pan and remix with a shovel to obtain a homogeneous batch.

The slump, air content, and unit weight of each batch were determined by ASTM Methods C 143-52, C 231-52T, and C 138-44, respectively. Concrete used for determining slump and air content was not returned to the batch to be used for molding specimens.

Molding Specimens

The specimens for freezing-and-thawing tests for each type of concrete were made in three rounds, three specimens per round. This provided nine specimens of a kind for any one freezing-and-thawing method.

The laboratories were instructed to prepare the molds and mold the specimens in the following manner: Make the molds watertight by sealing the joints with graphite grease and coat the inside surface of the mold with a uniformly thin film of SAE No. 20 lubricating oil; rod each layer 50 times for each square foot of area, with a $^5/_8$-in. bullet-nosed rod, and spade with 25 strokes on each side and 10 strokes on each end with a 6-in. blunt trowel; in placing the second layer, fill the mold $^1/_4$ in. above the top; after completion of rodding and spading the second layer, strike the top of the specimen off level with a straight edge advanced slowly along the beam and finish the surface with three strokes of a wood float; insert a metal identification strip in the top surface of each specimen.

Curing

Directions for curing the specimens were as follows: Immediately after molding, store the specimens in the moist room protected from dripping or direct fog spray and allow them to cure for 44 to 48 hr; immediately after stripping, weigh the specimens to the nearest gram in air and then under water maintained at 73 ± 1 F; then store them in water at 73 ± 3 F for 12 days; when the specimens are 14 days old, weigh them again, saturated surface dry, to the nearest gram in air and under water maintained at 73 ± 1 F; then test them for fundamental transverse frequency according to ASTM Method C 215 (5).

Freezing-and-Thawing Tests

The freezing-and-thawing tests were started when the specimens were 14 days old. Each participating laboratory used and followed, as closely as possible, one or more of the four ASTM methods of freezing and thawing, which are:

1. Tentative Method of Test for Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water, ASTM C 290-52T.
2. Tentative Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water, ASTM C 291-52T.
3. Tentative Method of Test for Resistance of Concrete Specimens to Slow Freezing and Thawing in Water or Brine, ASTM C 292-52T.
4. Tentative Method of Test for Resistance of Concrete Specimens to Slow Freezing in Air and Thawing in Water, ASTM C 310-53T.

Each participating laboratory reported typical time-temperature curves for the centers of the concrete specimens during the freezing-and-thawing cycles. Periodic readings of fundamental transverse frequency and of weight were taken on all specimens, and initial and final dynamic modulus of elasticity were calculated and reported. Relative dynamic modulus was calculated as the ratio of frequencies squared, as shown in each of the four freezing-and-thawing methods. Specimens were continued in the test

TABLE 1

COOPERATING LABORATORIES AND METHODS USED

Laboratory		Method			
No.	Name	C 290	C 291	C 292	C 310
1	U. S. Bureau of Reclamation	x	x	x	x
2	National Sand & Gravel Association		x		
3	Wisconsin State Highway Department				x
4	Purdue University		x		
5	Ohio State Highway Department		x		
6	U. S. Army Engineer Waterways Experiment Station	x			
7	National Crushed Stone Association		x		
8	U. S. Bureau of Public Roads			x	
9	University of Wisconsin				x
10	Portland Cement Association			x	x
11	Nebraska State Highway Department		x		
12	Hydro-Electric Power Commission of Ontario	x	x		
13	National Bureau of Standards	x	x	x	x
	Total	4	8	4	5

until they reached 300 cycles, or until the relative dynamic modulus reached 60 percent, and durability factors were calculated on this basis.

Steel bars for which a number of resonant frequencies for different modes of vibration were known were distributed to the laboratories, and were used to make periodic checks on the oscillators used in dynamic measurements. Records of these checks were reported.

PERFORMANCE OF APPARATUS

Thirteen laboratories participated in the program. Freezing-and-thawing methods used by the laboratories are indicated in Table 1. Two laboratories conducted tests by all four methods, and two performed tests by two methods, making a total of 21 combinations of methods and laboratories.

Curves showing the time-temperature performance of the apparatus used by each laboratory are shown in Figures 1, 2, 3, and 4. The data for these curves were obtained from thermocouples or resistance elements embedded in "dummy" specimens located at representative points in the apparatus and were recorded by means of various recording devices.

In all cases (except for some variations in individual cases which are noted later) the freezing-and-thawing apparatus and cycle conform to the applicable tentative method of test current at the time the tests were begun.[1] All laboratories which used Method C 292 used water rather than brine. Therefore, Methods C 290, C 291, C 292, and C 310 are hereafter referred to as "rapid-water," "rapid-air," "slow-water," and "slow-air," respectively.

Rapid-Water Systems

The four sets of curves for rapid-water apparatus (Method C 290) are shown in Figure 1. The "bars" curves represent the range of temperatures in the specimens, and the "tank" curve represents the ambient temperature in the freezing or thawing chamber. The values associated with the letters LG, HG, and HP on each of the sets of curves are the average durability factors obtained by that laboratory for the low-air good-aggregate, high-air good-aggregate, and high-air poor-aggregate concretes, respectively. The results of the tests are discussed more fully in succeeding sections.

Data about the freezing and thawing rates and temperatures for this method are given in Table 2. The thawing rates are quite uniform among the four laboratories, but the freezing rates vary widely, the rate for Laboratory 13 being approximately four times that for Laboratory 1. Test results for these two laboratories are, however, practically identical. The spread in temperatures at the thawing phase, and in time

[1] The requirements in the latest edition of the methods that the specimens be stored in water from the time of removal from the molds until the start of the tests, was followed in these tests, although it did not appear in the methods until later.

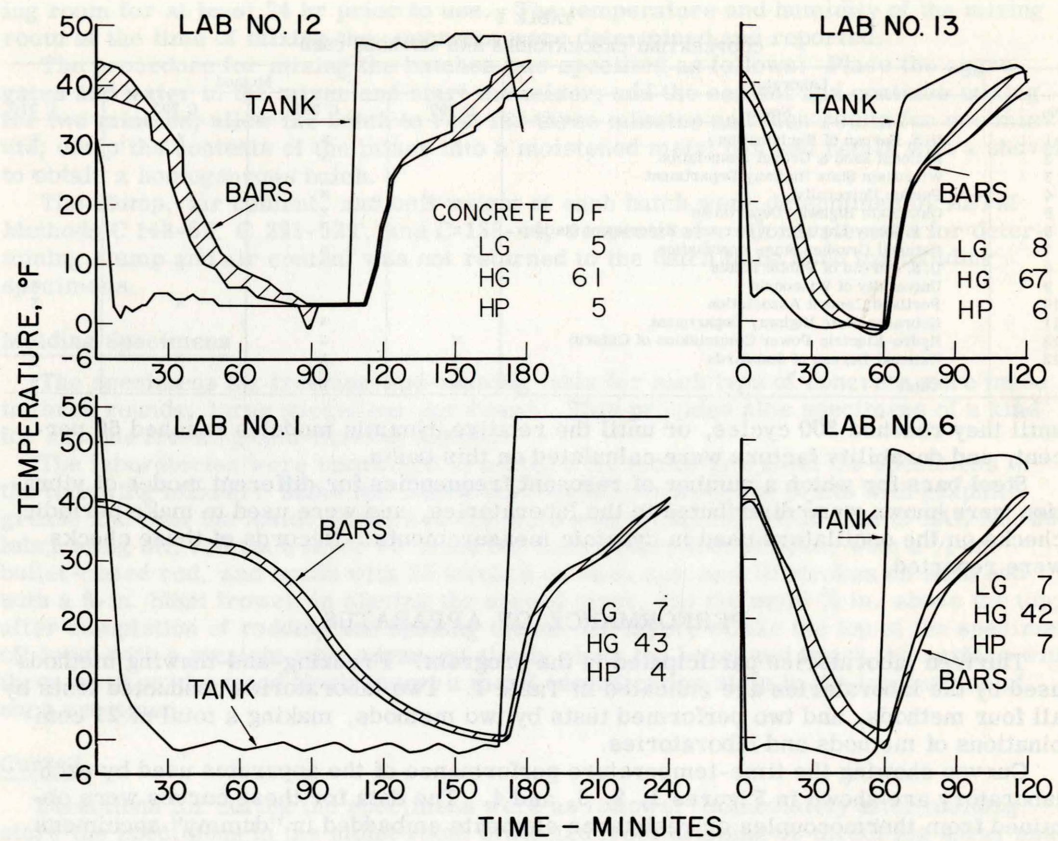

Figure 1. Time-temperature curves, rapid-water method (C 290).

required to reach the thawing temperature, appear in some cases to be outside the requirements of the specification (5). However, this does not appear to have had any significant effect on the results.

The usual practice with this method of freezing and thawing is to place the specimens in containers, either of rubber or metal, with water around the specimens, and to place the containers in a tank in which the freezing medium (either air or a liquid) is circulated. If the dimensions of the containers and the amount of water in them are reasonably uniform, uniform treatment of the specimens is relatively easy to obtain. Difficulty is sometimes experienced in melting the ice from around the tops of the specimens. Also, as testing progresses, specimens which do not fail early in the test decrease in volume by surface deterioration, so that it takes more water to fill the cans and more time to thaw the ice.

The apparatus used by three of these laboratories has been described elsewhere, as follows: Laboratory 1 (6), No. 6 (7), and No. 13 (8).

TABLE 2

PERFORMANCE DATA, RAPID-WATER METHOD (C 290)

Laboratory No.	Freezing Phase					Thawing Phase				
	Total Time (min)	Average Time to Reduce from 37 to 3 F (min)	Rate (deg/hr)	Temperature at End of Phase (F)		Total Time (min)	Average Time to Raise from 3 to 37 F (min)	Rate (deg/hr)	Temperature at End of Phase (F)	
				Max.	Min.				Max.	Min.
1	170	118	17	0.4	-0.6	70	54	44	40.4	39.2
6	60	38	54	1	-1.5	60	49	42	42.5	40
12	115	66	31	3	3	65	48	42	44	38
13	60	29	70	-1	-1.5	60	42	49	42	38.5

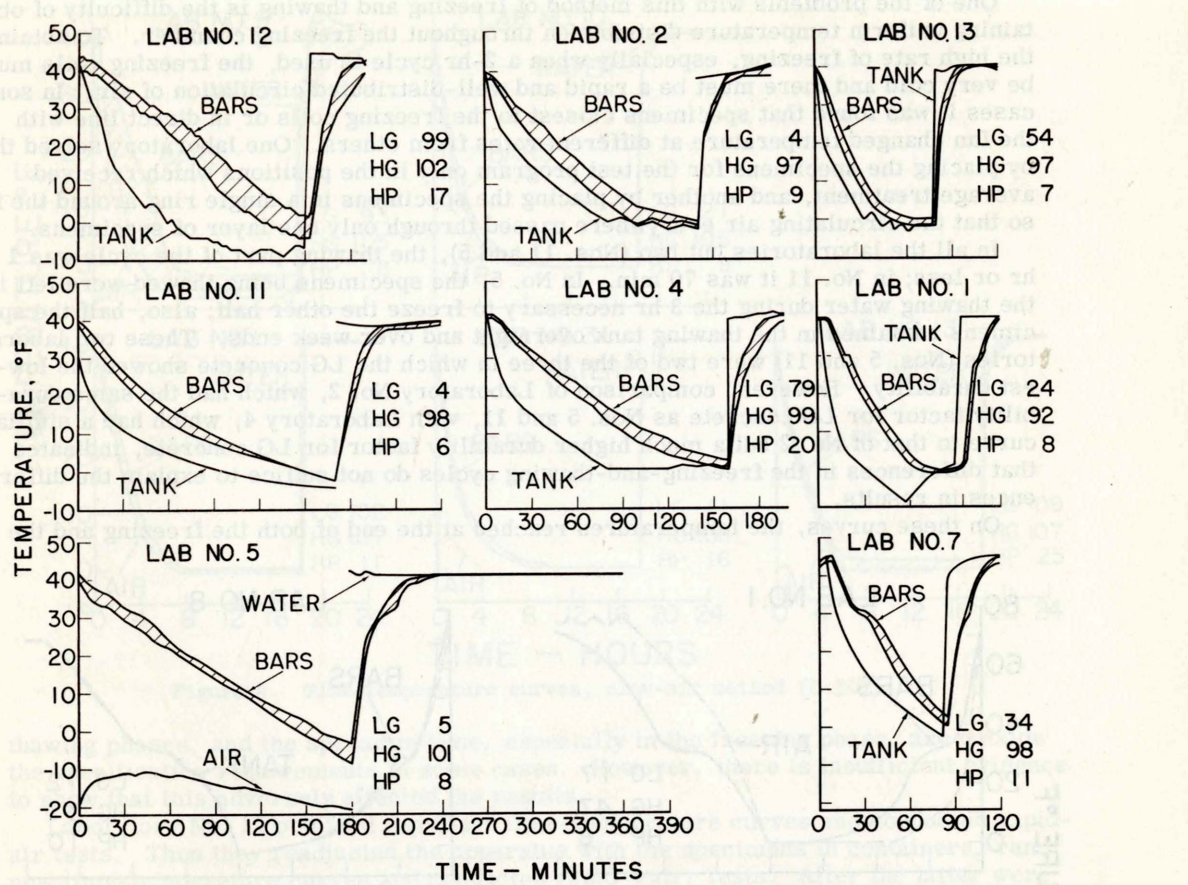

Figure 2. Time-temperature curves, rapid-air method (C 291).

Rapid-Air Systems

The curves for the eight laboratories which used the rapid-air method (C 291) are given in Figure 2, and pertinent performance data in Table 3. With this method both the freezing rate and thawing rate varied between laboratories. The differences in durability, however, do not appear to be related to the differences in cycle. This question is pursued further in later sections.

TABLE 3

PERFORMANCE DATA, RAPID-AIR METHOD (C 291)

Laboratory No.	Freezing Phase					Thawing Phase					Remarks
	Total Time (min)	Average Time to Reduce from 37 to 3 F (min)	Rate (deg/hr)	Temperature at End of Phase (F)		Total Time (min)	Average Time to Raise from 3 to 37 F (min)	Rate (deg/hr)	Temperature at End of Phase (F)		
				Max.	Min.				Max.	Min.	
1	90	48	41	0.4	-1.2	30	17	120	40	39.5	
2	135	90	22	0	-2	50	21	97	40	38	
4	160	117	17	2.8	0.2	40	24	87	41.5	40.5	
5	180	130	16	-3.5	-8.5	180	32	65	41.8	40.0	Freeze temp. too low; half of specimens in thaw water over night and week ends.
7	85	63	32	2.5	0.5	35	18	113	45.5	44	Thaw tempt. too high.
11	170	124	16	-2	-2	70	26	78	40	39	
12	151	102	20	2	-4	39	23	89	44	40	
12R	160	128	16	4	-3.5	40	27	76	43	38	Repeat test.
13	80	39	51	0	-2	40	13	157	40.2	39.8	

One of the problems with this method of freezing and thawing is the difficulty of obtaining uniform temperature distribution throughout the freezing chamber. To obtain the high rate of freezing, especially when a 2-hr cycle is used, the freezing coils must be very cold and there must be a rapid and well-distributed circulation of air. In some cases it was found that specimens closest to the freezing coils or in direct line with the fan changed temperature at different rates from others. One laboratory solved this by placing the specimens for the test program only in the positions which received average treatment, and another by placing the specimens in a single ring around the fan, so that the circulating air everywhere passed through only one layer of specimens.

In all the laboratories but two (Nos. 11 and 5), the thawing part of the cycle was 1 hr or less; in No. 11 it was 70 min. In No. 5, the specimens being thawed were left in the thawing water during the 3 hr necessary to freeze the other half; also, half the specimens remained in the thawing tank overnight and over week ends. These two laboratories (Nos. 5 and 11) were two of the three in which the LG concrete showed the lowest durability. However, comparison of Laboratory No. 2, which had the same durability factor for LG concrete as Nos. 5 and 11, with Laboratory 4, which had a similar curve to that of No. 2 but a much higher durability factor for LG concrete, indicates that differences in the freezing-and-thawing cycles do not suffice to explain the differences in results.

On these curves, the temperatures reached at the end of both the freezing and the

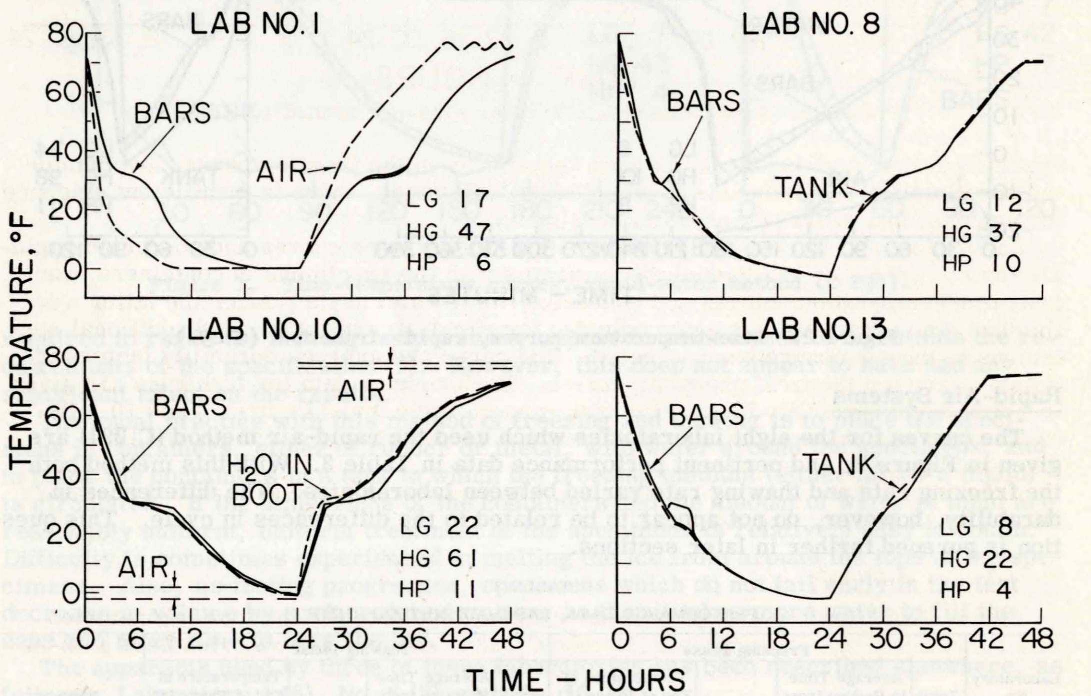

Figure 3. Time-temperature curves, slow-water method (C 292).

TABLE 4

PERFORMANCE DATA, SLOW-WATER METHOD (C 292)

Laboratory No.	Freezing Phase: Total Time (hr)	Freezing Phase: Average Time to Reduce from 70 to 3 F (hr)	Freezing Phase: Rate (deg/hr)	Freezing Phase: Temperature at End of Phase (F) Max.	Freezing Phase: Temperature at End of Phase (F) Min.	Thawing Phase: Total Time (hr)	Thawing Phase: Average Time to Raise from 3 to 70 F (hr)	Thawing Phase: Rate (deg/hr)	Thawing Phase: Temperature at End of Phase (F) Max.	Thawing Phase: Temperature at End of Phase (F) Min.
1	24	14.9	4.5	0	0	24	21.4	3.1	72	72
8	24	14.3	4.7	-3	-3	24	21.2	3.2	70.5	70.5
10	24	19.3	3.5	-0.5	-0.5	24	22.5	3.0	74.0	70.5
13	24	14.2	4.7	-2	-2	24	16.0	4.1	74	74

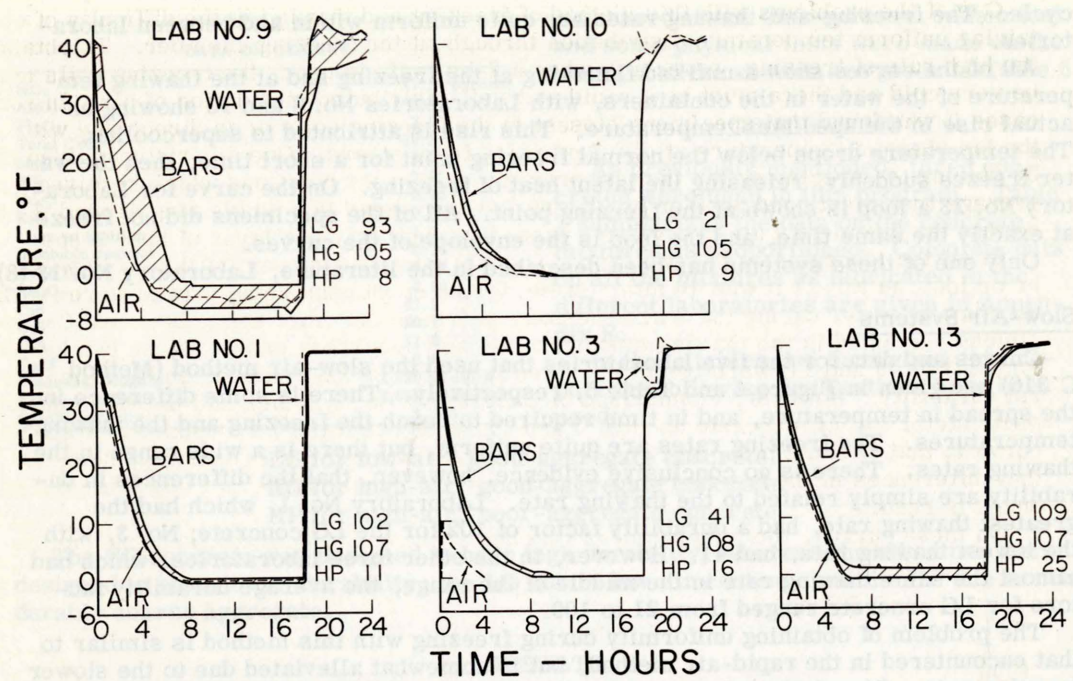

Figure 4. Time-temperature curves, slow-air method (C 310).

thawing phases, and the spread in time, especially in the freezing phase, are outside the specification requirements in some cases. However, there is insufficient evidence to show that this adversely affected the results.

Laboratory No. 12 obtained rapid-air time-temperature curves and conducted rapid-air tests. Then they readjusted the apparatus with the specimens in containers, ran new time-temperature curves and conducted rapid-water tests. After the latter were finished, the apparatus was again adjusted for rapid-air operation, and additional specimens of the LG concrete were tested. The curve and average durability factors in Figure 2 are for the first rapid-air series. Performance data for both runs are given in Table 3 and durability factors for both runs in Table 9 and Figures 9 and 10. Because there was not a significant difference in the performance, the second time-temperature curve is not given.

Apparatus of the following laboratories has been described elsewhere: Laboratory No. 2 (9), No. 7 (10), and No. 13 (8).

Slow-Water Systems

Figure 3 and Table 4 give performance curves and data for the four laboratories which conducted slow-water tests (Method C 292). All four laboratories used a 48-hr

TABLE 5

PERFORMANCE DATA, SLOW-AIR METHOD (C 310)

Laboratory No.	Freezing Phase: Total Time (hr)	Freezing Phase: Average Time to Reduce from 37 to 3 F (hr)	Freezing Phase: Rate (deg/hr)	Freezing Phase: Temperature at End of Phase (F) Max.	Freezing Phase: Temperature at End of Phase (F) Min.	Thawing Phase: Total Time (hr)	Thawing Phase: Average Time to Raise from 3 to 37 F (hr)	Thawing Phase: Rate (deg/hr)	Thawing Phase: Temperature at End of Phase (F) Max.	Thawing Phase: Temperature at End of Phase (F) Min.	Remarks
1	17.1	5.4	6.3	0.3	-0.6	6.9	0.35	97	40.2	40.0	Thawing too fast.
3	18	5.3	6.4	0.0	0.0	6	1.8	19	40.0	40.0	
9	18	5.0	6.9	-2.0	-7.0	6	1.1	31	47.0	38.0	Freeze temp. too low, thaw temp. too high.
10	18	4.8	7.1	-1.0	-1.0	6	1.2	28	41.0	41.0	
13	18	4.8	7.2	1.0	-0.7	6	1.2	28	40.2	40.1	

cycle. The freezing-and-thawing rates are quite uniform within and between laboratories.

All of the curves show a marked flattening at the freezing and at the thawing temperature of the water in the containers, with Laboratories No. 8 and 13 showing an actual rise in the specimen temperature. This rise is attributed to supercooling. The temperature drops below the normal freezing point for a short time, then the water freezes suddenly, releasing the latent heat of freezing. On the curve for Laboratory No. 13 a loop is shown at the freezing point. All of the specimens did not freeze at exactly the same time, and the loop is the envelope of the curves.

Only one of these systems has been described in the literature, Laboratory No. 13 (8).

Slow-Air Systems

Curves and data for the five laboratories that used the slow-air method (Method C 310) are given in Figure 4 and Table 5, respectively. There is some difference in the spread in temperature, and in time required to reach the freezing and the thawing temperatures. The freezing rates are quite uniform, but there is a wide range in the thawing rates. There is no conclusive evidence, however, that the differences in durability are simply related to the thawing rate. Laboratory No. 1, which had the greatest thawing rate, had a durability factor of 102 for the LG concrete; No. 3, with the lowest thawing rate, had 41. However, in the other three laboratories, which had almost the same thawing rate in the middle of the range, the average durability factors for LG concrete ranged from 21 to 109.

The problem of obtaining uniformity during freezing with this method is similar to that encountered in the rapid-air method, but is somewhat alleviated due to the slower freezing rate. Circulation of air and location of specimens in the chamber need serious attention, however.

The apparatus of Laboratory No. 13 has been described (8).

MATERIALS

Aggregates

The "good" coarse aggregate used in concretes LG and HG was a good grade of typical Northeast Atlantic Coastal Plain gravel composed almost entirely of a mixture of quartzite and vein quartz pebbles. It contained less than 1 percent of ferruginous sandstone bonded with limonite, and a very few particles of high-quartz conglomerate with the bonding material consisting of a mixture of silica and limonite, with some gneiss and feldspar and probably a little chert. In processing the aggregate for use in the freezing-and-thawing tests, the latter classes of materials were removed by handpicking, leaving only the essentially pure mixture of quartz and quartzite pebbles. In shape, the gravel was subangular with rounded corners and edges, to ellipsoidal, with fairly smooth but irregular surface texture.

The "poor" coarse aggregate in the HP concrete was a soft, fine-grained, finely-porous, olive-gray to buff to almost white, shaly, thin-bedded argillaceous limestone, which no one familiar with the behavior of aggregates in a rapid-cycle water freezer would expect to last. It was suspected of being more finely porous than cement paste. It was made up of several varieties of dolomite and dolomitic limestone in various stages of weathering, limestone, and a small amount of chalcedonic chert. It contained a small amount of clay, mainly illite, but no montmorillonite or other swelling clays.

The fine aggregate was a rounded natural sand containing about 90 percent quartz and 6 percent chert, the latter essentially confined to the sizes retained on the No. 16 sieve. The chert in the upper sizes was generally porous.

A complete petrographic analysis of the limestone and more detailed information on the sand are given in Appendix D.

Cement

The cement used was a blend of equal amounts by weight of four Type I cements purchased in the Chicago area. Chemical and some physical tests were made on the blend, and the results are given in Table 6.

TABLE 6

DATA ON CEMENT

SiO_2	21.3 percent
Al_2O_3	6.0
Fe_2O_3	2.7
Total CaO	62.8
MgO	2.5
SO_3	2.0
Na_2O	0.22
K_2O	0.67
Loss on ignition	1.3
Insoluble residue	0.14
Free CaO	0.67
Mn_2O_3	0.30
C_3S	41.2
C_2S	30.1
C_3A	11.2
C_4AF	8.3
Fineness, Wagner	1,620 sq cm/g
Fineness, Blaine	3,060 sq cm/g
Specific gravity	3.145

CONCRETES

As previously mentioned, three concretes were used in this program. Table 7 summarizes the data on the concrete mixtures as proportioned. Complete data on all the mixtures as fabricated in the different laboratories are given in Appendix E.

In these tables and throughout this report the following designations have been used:

LG for low-air, good-aggregate concrete.
HG for high-air, good-aggregate concrete.
HP for high-air, poor-aggregate concrete.

The HG concrete was designed to have high durability, whereas the other two were designed to have lower durability, the LG due to low air content, and the HP due to non-durable coarse aggregate.

RESULTS

Data from this program were extremely voluminous. There were 576 specimens, on each of which a whole series of dynamic modulus and weight readings were taken. Tables showing the initial and final readings for each of these specimens are given in Appendix E, and two complete sets of data sheets showing all readings taken are on file in the library of the Highway Research Board, Washington, D.C.

TABLE 7

DATA ON CONCRETES[1]

Concrete	Aggregate	Mixture Proportions, by Weight	W/C Ratio, by Weight	Air Content (percent vol)
LG	Siliceous gravel	1:2.7:3.5	0.52	2½ - 3
HG	Siliceous gravel	1:2.4:3.5	0.47	6 - 7
HP	Porous limestone	1:2.5:3.3	0.61	6 - 7

[1]Cement content, 5.5 ± 0.1 bags per cu yd; desired slump, 2-3 in.; air-entraining agent, to produce desired air content.

The ASTM freezing-and-thawing methods include the recommendation that "the average of the results on each group of similar specimens be plotted as curves showing the value of relative modulus of elasticity against time expressed as number of cycles of freezing and thawing." This method of reducing the data to manageable and graphic form was followed, except that a confidence interval covering each average was plotted instead of the actual average.

As freezing-and-thawing tests progressed, the specimens were periodically removed and tested for fundamental transverse frequency, and the relative dynamic modulus was calculated, as previously mentioned. The average of the nine specimens[2] in a given method was calculated, as recommended in the ASTM freezing-and-thawing methods (5). To show the spread in results from individual specimens, the 95 percent

[2]In some cases one or two specimens were eliminated from consideration, either because the batches from which they came were outside the specifications in some way (usually too low or too high air content), because one specimen was broken in handling, or because an individual specimen differed so far from the others that it could be considered as not belonging to the same statistical population. In the latter case, the criterion given by Dixon and Massey (11) was used in deciding when a specimen differed sufficiently from the others to be rejected. Table 9 shows the number of specimens used in calculating the durability factors. In each case the same number of specimens as shown in Table 9 was used in the bar graphs and the confidence-interval curves.

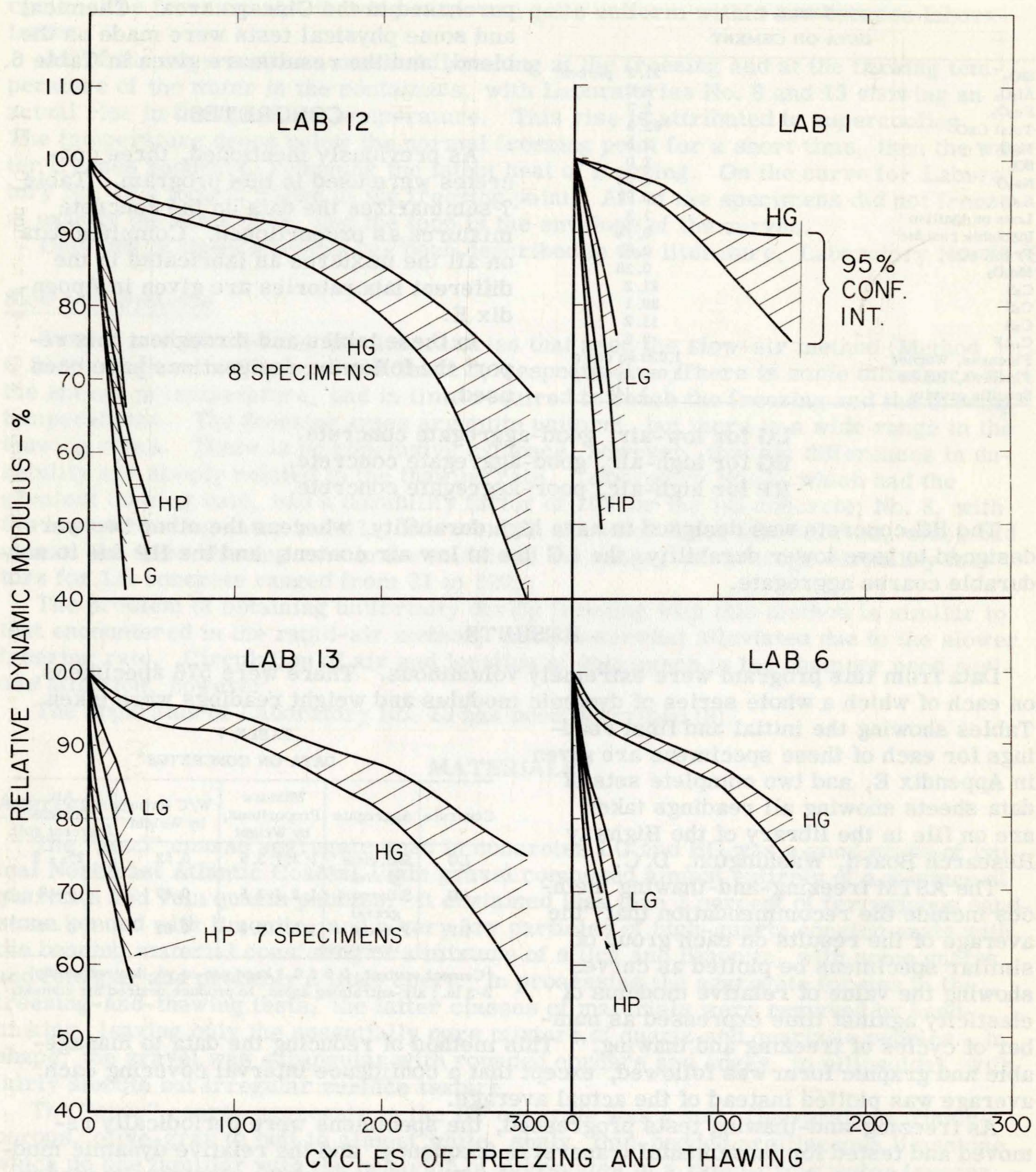

Figure 5. Relation between relative dynamic modulus and cycles of freezing and thawing, rapid-water method (C 290).

confidence limits[3] of the average were also calculated. These limits are plotted in Figures 5, 6, 7, and 8. Deterioration of the specimens is shown by the downward trend of the curves, and the spread by the vertical width of the cross-hatched area between the heavy lines, which represents the confidence interval. The average lies

[3] The 95 percent confidence limits for the mean are the limits of the region on either side of the sample mean within which the true mean of the population from which this sample is drawn may be assumed to lie with a 95 percent probability of being correct. The region between these limits (cross-hatched on the curves and bars) is called the confidence interval.

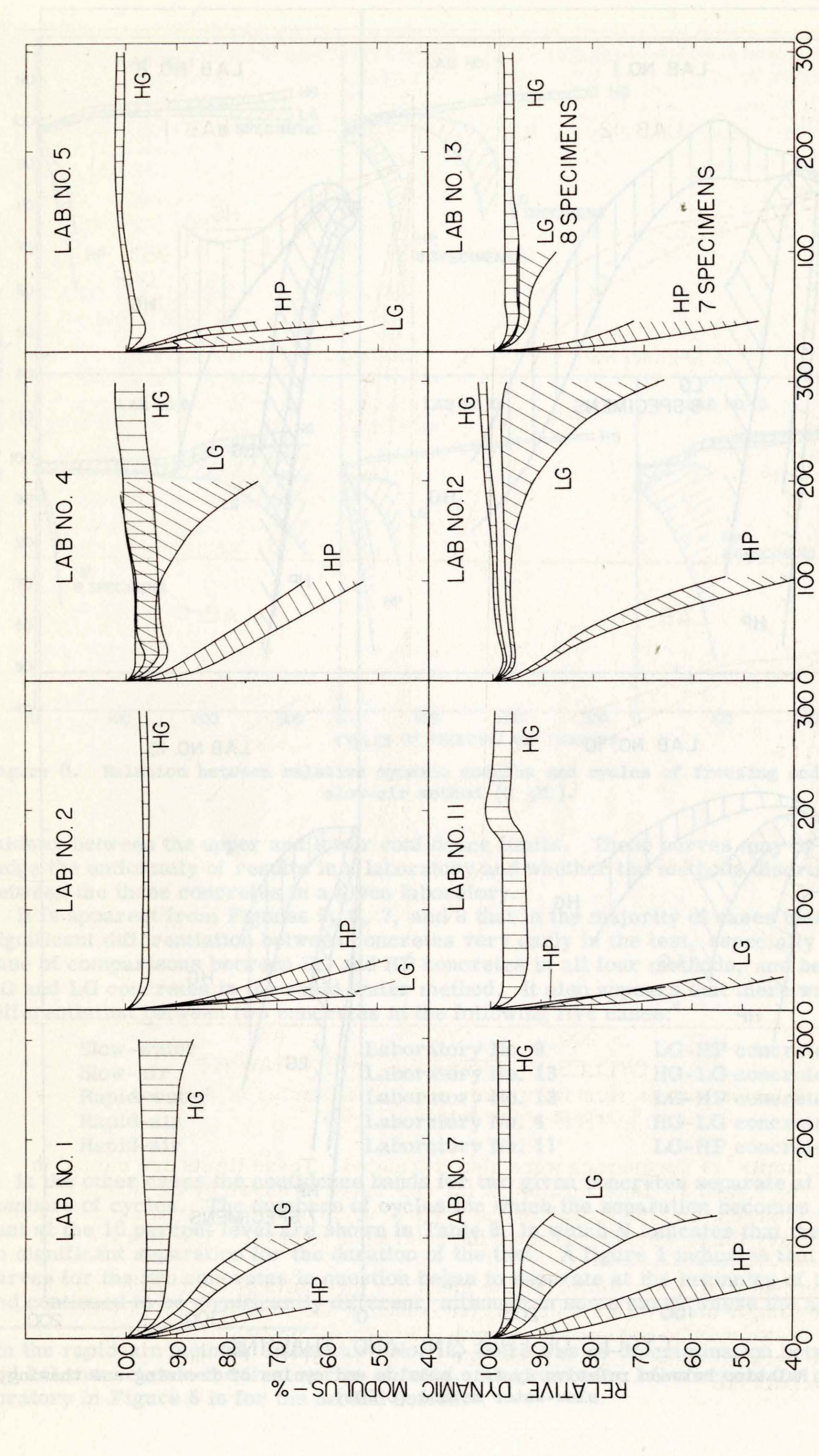

Figure 6. Relation between relative dynamic modulus and cycles of freezing and thawing, rapid-air method (C 291).

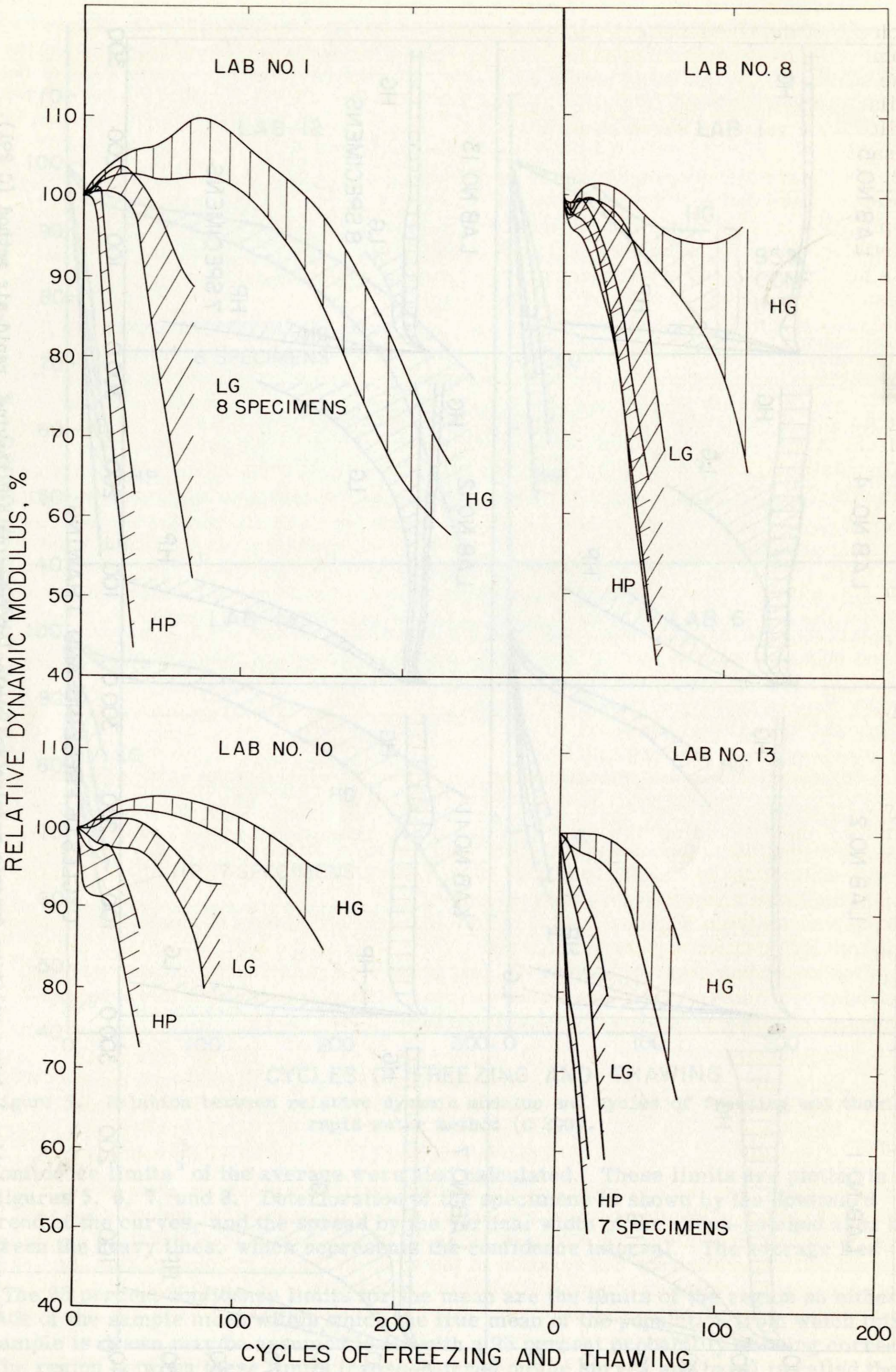

Figure 7. Relation between relative dynamic modulus and cycles of freezing and thawing, slow-water method (C 292).

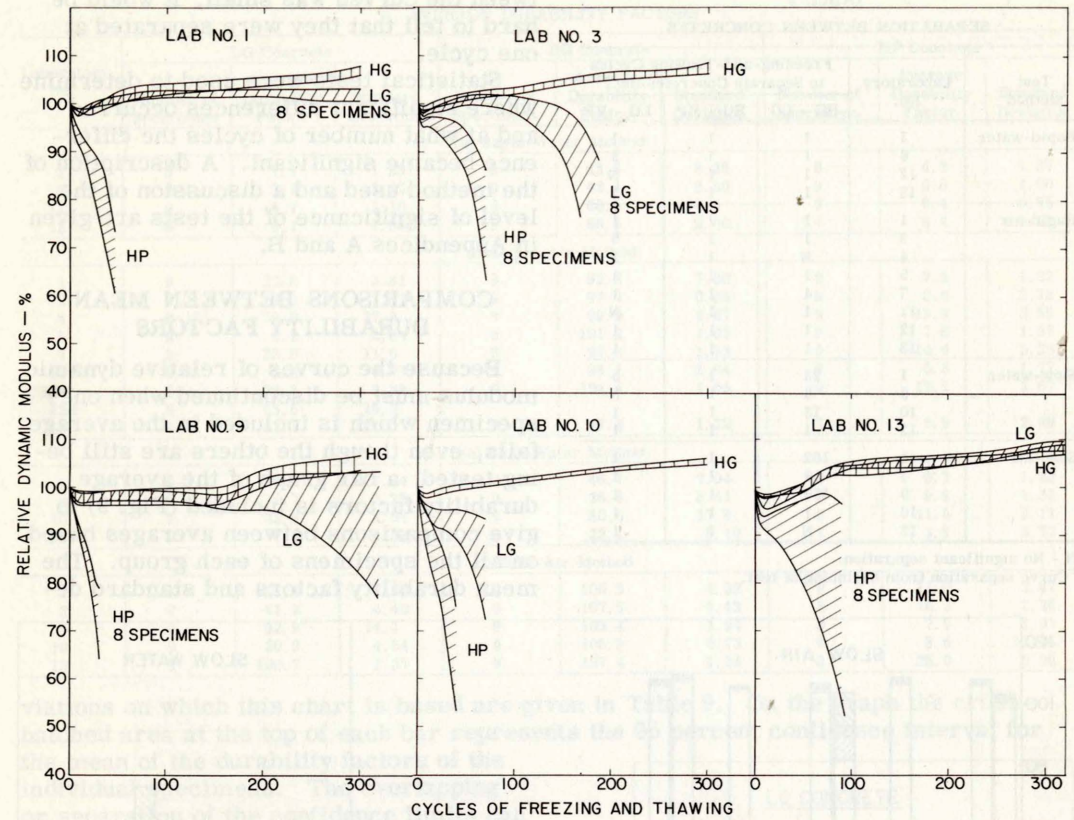

Figure 8. Relation between relative dynamic modulus and cycles of freezing and thawing, slow-air method (C 310).

midway between the upper and lower confidence limits. These curves may be used to judge the uniformity of results in a laboratory and whether the methods discriminated between the three concretes in a given laboratory.

It is apparent from Figures 5, 6, 7, and 8 that in the majority of cases there was a significant differentiation between concretes very early in the test, especially in the case of comparisons between HG and HP concretes in all four methods, and between HG and LG concretes in the rapid-water method. It also appears that there was no differentiation between two concretes in the following five cases:[4]

Slow-water	Laboratory No. 8	LG-HP concretes
Slow-air	Laboratory No. 13	HG-LG concretes
Rapid-water	Laboratory No. 12	LG-HP concretes
Rapid-air	Laboratory No. 4	HG-LG concretes
Rapid-air	Laboratory No. 11	LG-HP concretes

In the other cases the confidence bands for two given concretes separate at various numbers of cycles. The numbers of cycles for which the separation becomes significant at the 10 percent level are shown in Table 8, in which N indicates that there was no significant separation for the duration of the test. A figure 1 indicates that the curves for the two concretes in question began to separate at the beginning of the test and continued to be significantly different, although in some cases where the angle be-

[4] In the rapid-air method, Laboratory No. 12, there was no discrimination between HG and LG concretes in the first series of tests. The curve for LG concrete for this laboratory in Figure 6 is for the second series.

TABLE 8

SEPARATION BETWEEN CONCRETES

Test Method	Laboratory No.	Freezing-and-Thawing Cycles to Separate Concretes (no.)[1]		
		HG - LG	HG - HP	LG - HP
Rapid-water	1	1	1	1
	6	1	1	5
	12	1	1	N
	13	1	1	1
Rapid-air	1	1	1	1
	2	1	1	5
	4	N	1	1
	5	1	1	1
	7	4	1	1
	11	1	1	N
	12	1	1	1
	13	1	1	1
Slow-water	1	23	1	5
	8	8	1	N
	10	13	1	1
	13	1	1	1
Slow-air	1	102	1	1
	3	59	1	1
	9	168	1	1
	10	1	1	1
	13	N	1	1

N - No significant separation.
[1]Curve separation from beginning of test.

tween the curves was small, it would be hard to tell that they were separated at one cycle.

Statistical tests were used to determine where significant differences occurred and at what number of cycles the difference became significant. A description of the method used and a discussion of the level of significance of the tests are given in Appendices A and B.

COMPARISONS BETWEEN MEAN DURABILITY FACTORS

Because the curves of relative dynamic modulus must be discontinued when one specimen which is included in the average fails, even though the others are still being tested, a bar graph of the average durability factors is included (Fig. 9) to give comparisons between averages based on all the specimens of each group. The mean durability factors and standard de-

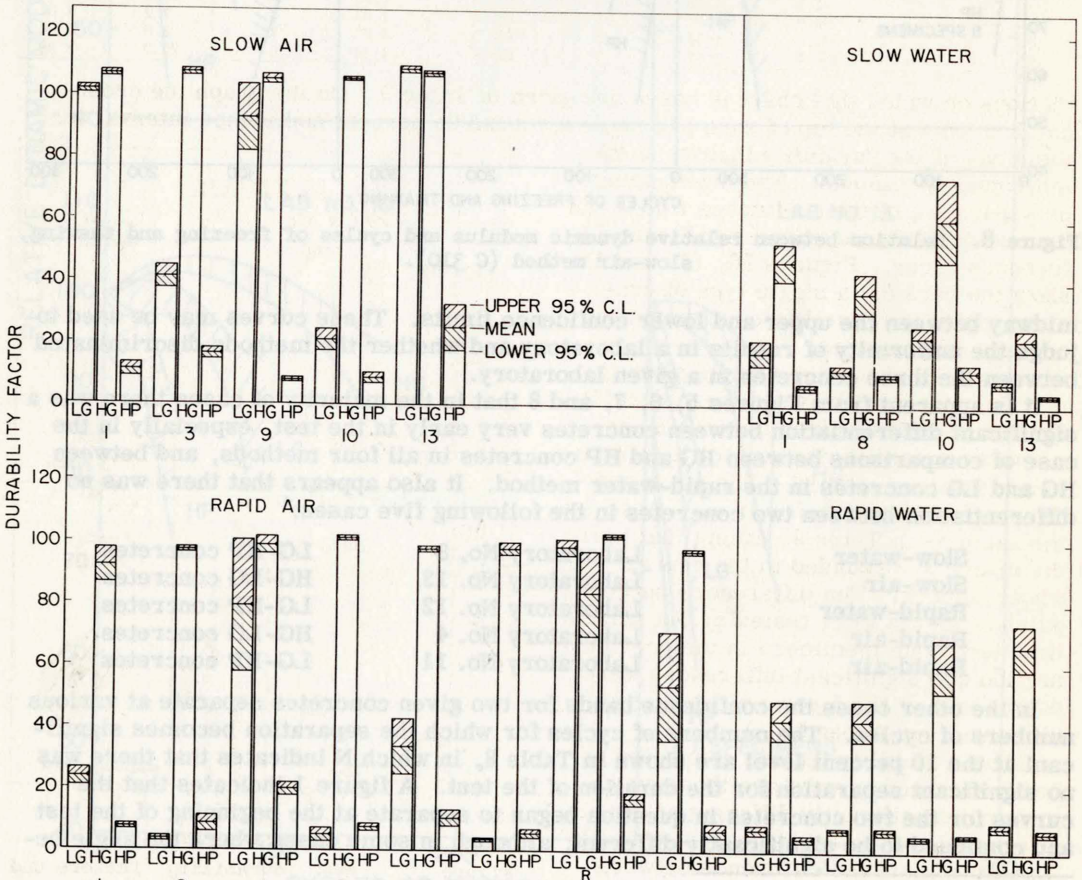

Figure 9. Mean durability factors and 95 percent confidence intervals, all concretes.

TABLE 9

AVERAGE DURABILITY FACTORS

Laboratory No.	LG Concrete: Number of Specimens	LG Concrete: Average Durability Factor	LG Concrete: Standard Deviation	HG Concrete: Number of Specimens	HG Concrete: Average Durability Factor	HG Concrete: Standard Deviation	HP Concrete: Number of Specimens	HP Concrete: Average Durability Factor	HP Concrete: Standard Deviation
(a) Rapid-Water Method									
1	9	7.1	1.88	9	42.6	8.38	9	4.3	1.37
6	9	7.1	1.17	9	42.4	8.30	9	6.9	1.60
12	9	4.7	1.10	8	60.5	10.3	9	5.4	0.75
13	9	8.1	1.88	9	66.5	9.80	7	6.4	1.23
(b) Rapid-Air Method									
1	9	23.6	3.81	9	92.2	7.30	9	7.5	1.22
2	9	3.6	1.17	9	97.4	0.98	9	8.6	2.78
4	9	79.2	27.9	9	99.0	3.67	9	19.9	2.68
5	9	5.2	2.84	9	101.2	1.02	9	7.6	1.57
7	9	33.8	11.6	9	97.8	1.13	9	10.6	3.36
11	9	3.8	0.77	9	98.1	2.64	9	5.8	1.77
12	9	98.5	3.38	9	102.4	1.05	9	17.1	2.67
12R	9	83.6	16.9						
13	8	53.7	21.0	9	97.3	1.22	7	6.9	2.49
(c) Slow-Water Method									
1	8	17.2	4.94	9	46.7	7.94	9	6.3	1.23
8	9	11.7	2.25	9	36.6	8.41	9	9.9	1.33
10	9	22.5	4.51	9	60.6	17.6	9	11.4	3.11
13	9	7.7	1.58	9	22.1	5.10	7	3.8	0.72
(d) Slow-Air Method									
1	8	101.8	1.57	9	106.9	1.32	9	11.0	2.87
3	8	41.2	4.43	9	107.5	1.43	8	16.3	2.28
9	9	92.9	14.1	9	105.4	1.94	8	7.9	1.01
10	9	20.9	4.54	9	105.5	0.73	9	8.6	2.06
13	9	108.7	1.37	9	107.4	1.14	8	25.0	8.98

viations on which this chart is based are given in Table 9. On the graph the cross-hatched area at the top of each bar represents the 95 percent confidence interval for the mean of the durability factors of the individual specimens. The overlapping or separation of the confidence limits can be used to estimate where significant differences occur. Figures 10, 11, and 12 show the bars for a single type of concrete together to facilitate comparisons between laboratories.

Figure 13 shows the results of statistical comparisons between mean durability factors. The values in circles are the mean durability factors for a concrete in a laboratory method. The mean and the number of specimens in each case are the same as in Table 9, except that here the means are rounded to the nearest whole number. The differences between pairs of means were tested by the statistical technique mentioned in the previous section and significant differences were determined at the 5 percent level of significance (see Appendix A).

Mean durability factors connected by heavy bars and arrows are those which were not significantly different at the significance level selected; that is, those in which the observed difference between means is not great enough to indicate that the means of the two populations in question

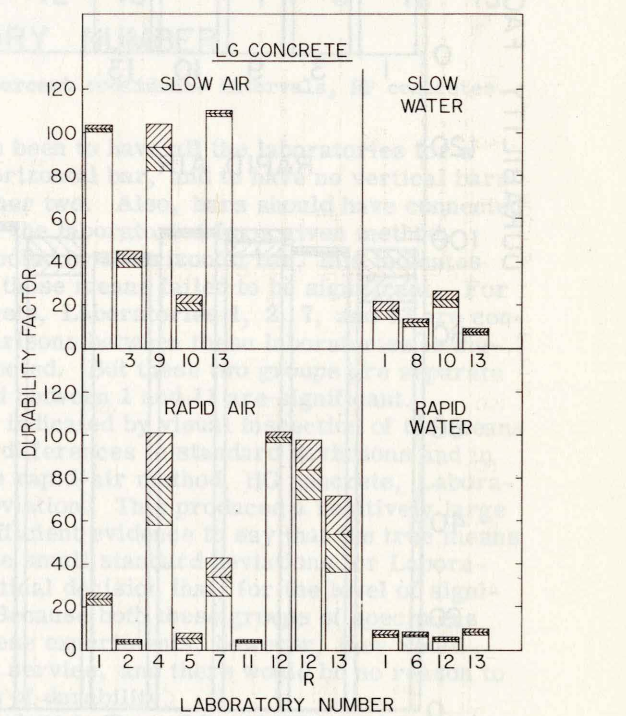

Figure 10. Mean durability factors and 95 percent confidence intervals, LG concretes.

were not the same. The horizontal bars indicate laboratories which gave the same results on the same concrete, and the vertical bars indicate concrete which showed the same results in the same laboratory in a given method.

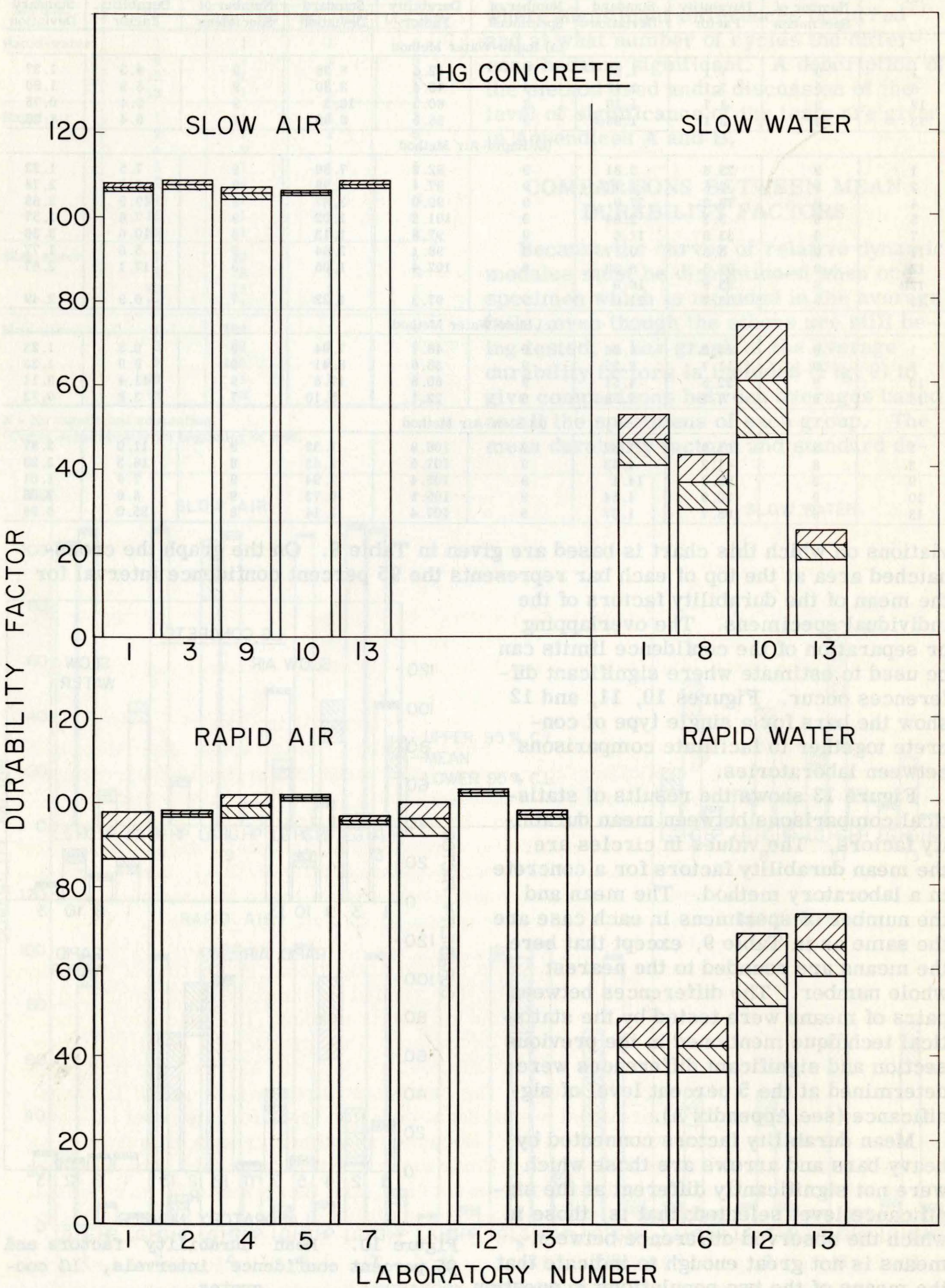

Figure 11. Mean durability factors and 95 percent confidence intervals, HG concretes.

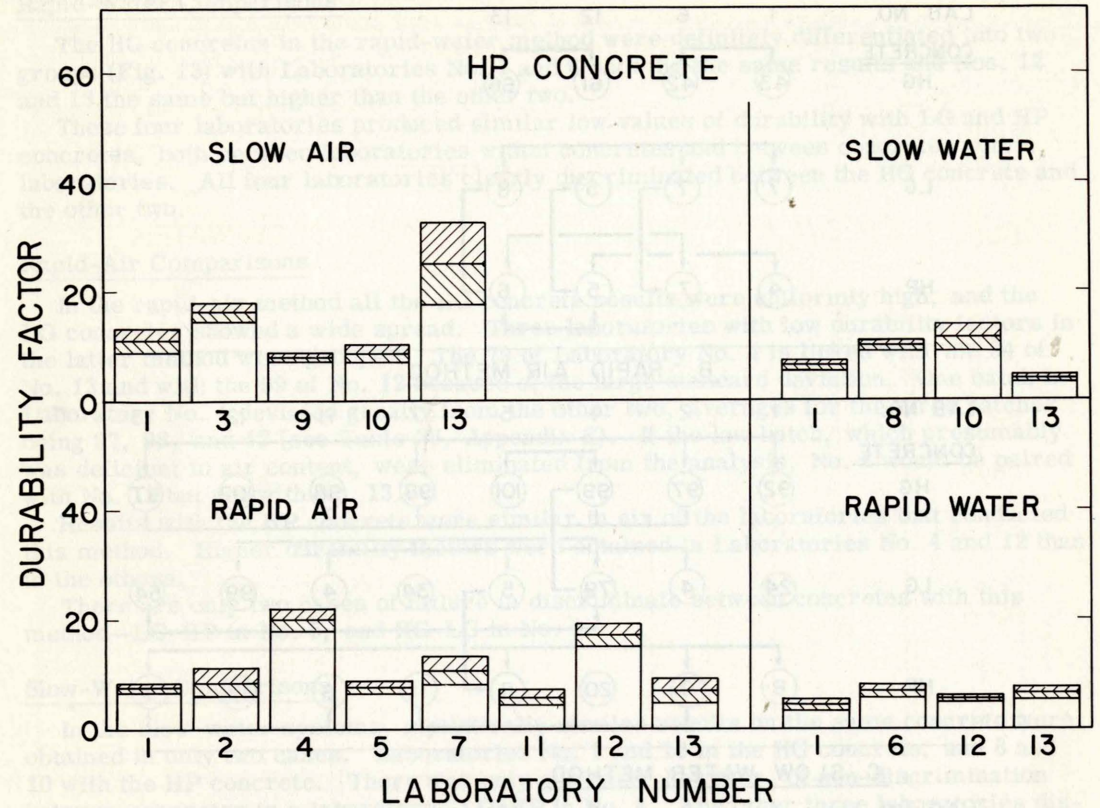

Figure 12. Mean durability factors and 95 percent confidence intervals, HP concretes.

The ideal result of these tests would have been to have all the laboratories for a given concrete and method connected by a horizontal bar, and to have no vertical bars connecting HG concrete with either of the other two. Also, bars should have connected LG and HP concretes in either all or none of the laboratories for a given method.

Whenever three or more means are connected by a horizontal bar, this indicates that the differences for all possible pairs of those means failed to be significant. For example, in the rapid-air method, HG concrete, Laboratories 1, 2, 7, and 13 are connected, indicating that none of the six comparisons between these laboratories is significant. Also 2, 4, 7, 11, and 13 are connected. But these two groups are separate because the differences between 1 and 4, and between 1 and 11 are significant.

There are some apparent inconsistencies indicated by visual inspection of the means in this figure. These are largely caused by differences in standard deviations and in numbers of specimens. For example, in the rapid-air method, HG concrete, Laboratory No. 4 had a relatively large standard deviation. This produced a relatively large uncertainty in its mean, thus there was insufficient evidence to say that the true means for Laboratories 4 and 5 were different. The small standard deviations for Laboratories 5 and 12, however, permitted a statistical decision that, for the level of significance chosen, the means were different. Because both these groups of specimens had such a high durability as measured in these experiments, however, they would both be expected to perform satisfactorily in service, and there would be no reason to choose one rather than the other on the basis of durability.

Similar considerations apply to the comparison between LG and HP concretes for Laboratories No. 5 and 11 in the rapid-air method. The durability for these four groups of specimens was so low that they would all probably fail at an early age in service.

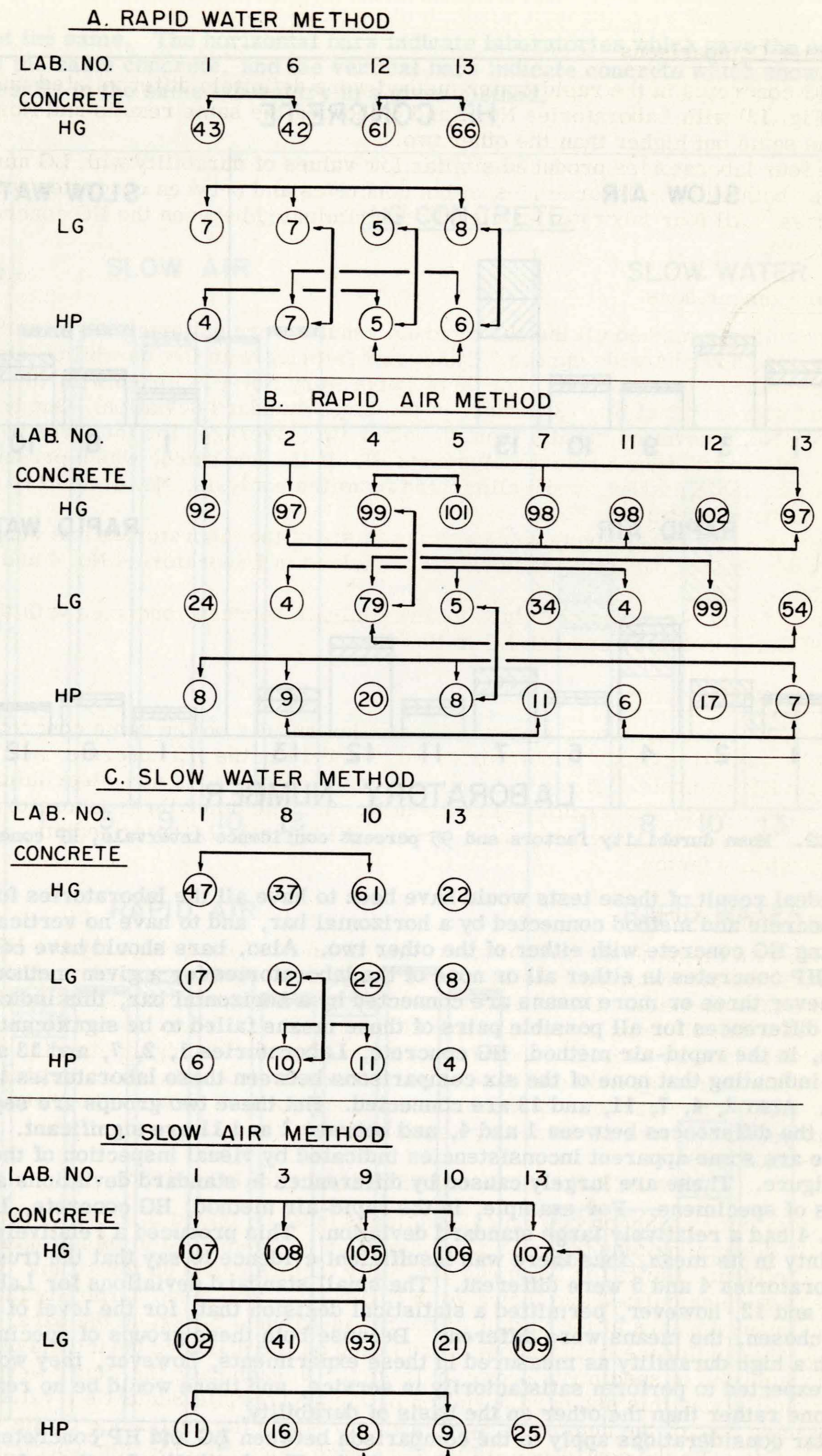

Figure 13. Comparisons of laboratory mean durability factors at 5 percent significance level.

Rapid-Water Comparisons

The HG concretes in the rapid-water method were definitely differentiated into two groups (Fig. 13) with Laboratories No. 1 and 6 showing the same results and Nos. 12 and 13 the same but higher than the other two.

These four laboratories produced similar low values of durability with LG and HP concretes, both between laboratories within concretes and between concretes within laboratories. All four laboratories clearly discriminated between the HG concrete and the other two.

Rapid-Air Comparisons

In the rapid-air method all the HG concrete results were uniformly high, and the LG concretes showed a wide spread. Three laboratories with low durability factors in the latter method were grouped. The 79 of Laboratory No. 4 is linked with the 54 of No. 13 and with the 99 of No. 12 because of the large standard deviation. One batch in Laboratory No. 4 deviated greatly from the other two, averages for the three batches being 97, 98, and 42 (see Table 36, Appendix E). If the low batch, which presumably was deficient in air content, were eliminated from the analysis, No. 4 would be paired with No. 12 but not with No. 13.

Results with the HP concrete were similar in six of the laboratories that conducted this method. Higher durability factors were obtained in Laboratories No. 4 and 12 than in the others.

There are only two cases of failure to discriminate between concretes with this method—LG-HP in No. 5, and HG-LG in No. 4.

Slow-Water Comparisons

In the slow-water systems, statistically similar results on the same concrete were obtained in only two cases. Laboratories No. 1 and 10 in the HG concrete, and 8 and 10 with the HP concrete. There was only one case, however, of non-discrimination between concretes in a laboratory—LG-HP in No. 8. The other three laboratories discriminated between the concretes in the order, HG highest, LG intermediate, and HP lowest durability factor.

Slow-Air Comparisons

Results with the slow-air method were similar and uniformly high for the HG concrete in all five laboratories. As in the rapid-air method, the greatest variation was among the LG concretes. Only Laboratories No. 1 and 9 showed statistically similar results, with No. 13 being higher and Nos. 3 and 10 lower. There were two pairs of low durability factors with HP concrete, with two laboratories higher than the others.

Here again there was only one case of non-discrimination between concretes—HG-LG in No. 13. The other four laboratories all discriminated between the three concretes in the same order of durability as was found in the slow-water method.

NUMBER OF SPECIMENS REQUIRED FOR TEST

To obtain information on how many specimens must be tested in order to provide significant discriminations between concretes such as those used in this program, 95 percent confidence limits for the mean durability factors based on three, six, and nine specimens were calculated and indicated in Figure 14. The mean durability factor for nine specimens appears at the middle of the cross-hatched region on the bars. (In Figure 9, the confidence limits shown were based on the standard deviations obtained from the numbers of specimens shown in Table 9. In each case the limits were calculated by multiplying this standard deviation by the appropriate Student's t-value divided by the square root of the number of specimens for which the confidence limits were desired. In this case the confidence limits were each calculated for nine specimens, and the nine-specimen confidence limits in Figure 15 coincide with those in Figure 9 only in the cases where nine specimens were actually used.)

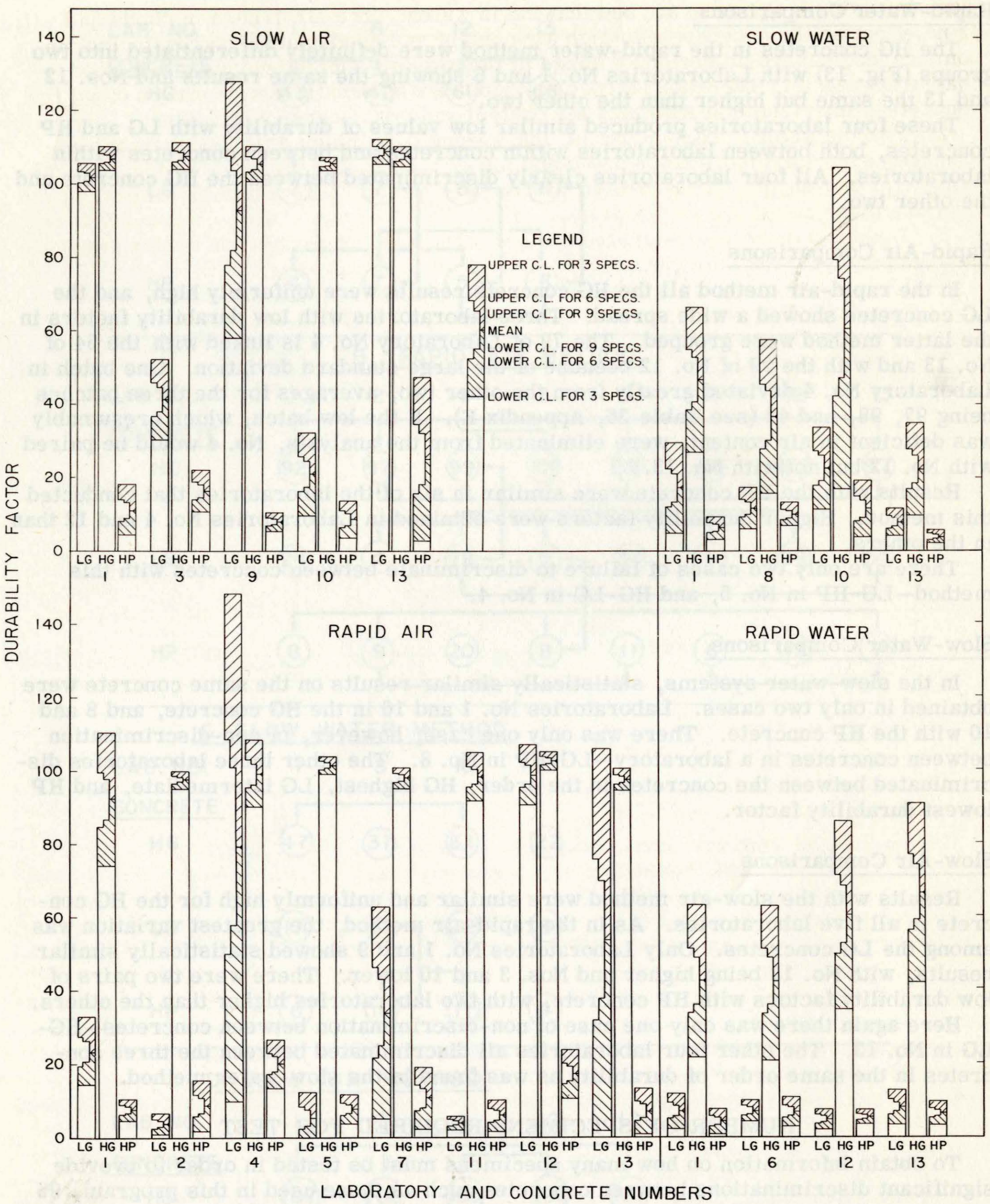

Figure 14. Confidence intervals for mean durability factors for different numbers of specimens.

Comparing these bars and the various confidence limits, it appears that testing six instead of nine specimens would probably have made little difference in the comparisons, but the use of only three would have failed to reveal many significant differences between laboratories and between concretes in a laboratory. (It must be borne in mind that the confidence limits given in Figure 15 are based on estimates of the standard deviations obtained from particular samples of nine specimens. If any other samples from the same populations had been tested, the standard deviations and confidence limits obtained therefrom would have been different. In spite of these uncertainties in standard deviation, however, the bars in Figure 15 give an indication of how the confidence intervals are widened by the use of a reduced number of specimens, especially if the variability of the specimens is large.)

With these data and the standard deviation calculated from them, it appears that a sample of nine specimens was adequate to determine the significant differences in most cases. As the number of specimens is increased, smaller decrements of the confidence level occur for a given increment in number of specimens, and an increase above nine, in most of the cases examined here, would have had little effect on the significant differentiations.

VARIABILITY OF FREEZING-AND-THAWING RESULTS

The data from this program illustrate the frequently observed fact that the variability of freezing-and-thawing data is greatest when the mean durability is in the mid-range of durability factors. Figure 15 shows the standard deviation of the LG specimens for each laboratory method plotted against the mean durability factor. The standard deviation appears to reach a maximum at a durability factor of 60 to 70.

When the data for all concretes are plotted in this manner, the curve is similar to that shown. However, the results shown here for a single concrete illustrate an interesting problem.

If resistance to freezing and thawing as measured in the laboratory is a characteristic of the concrete, and an adequate test method for measuring it had been used, the durability factor should have been about the same for all these LG specimens. That

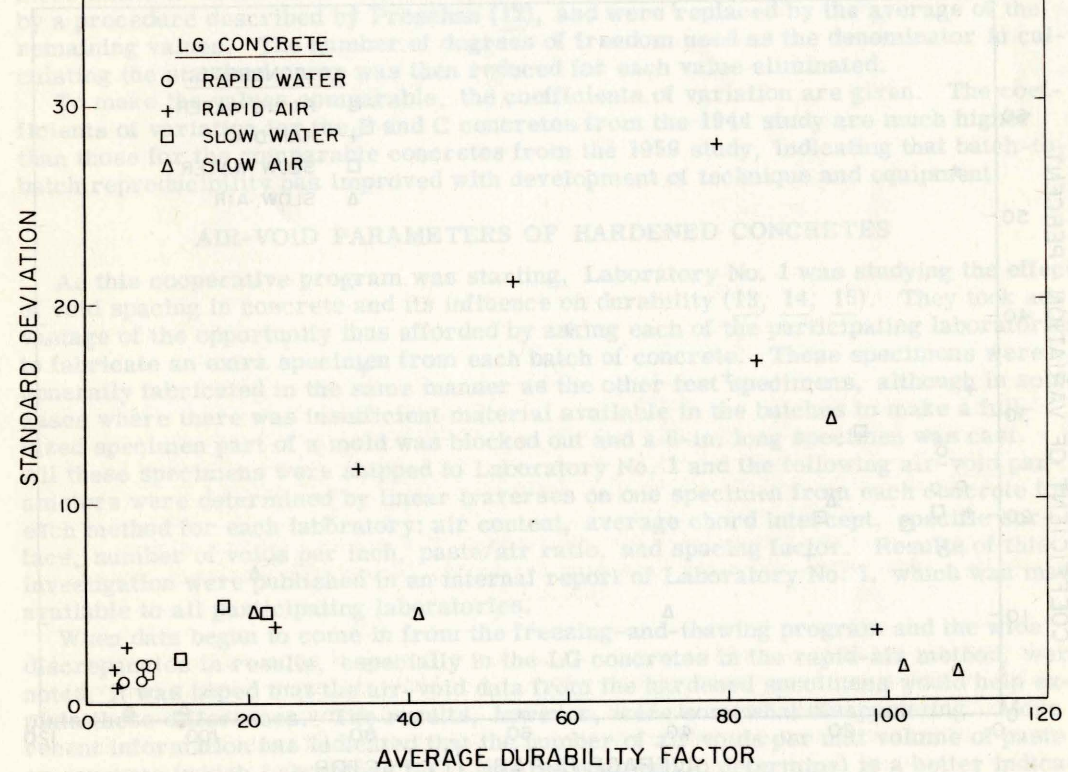

Figure 15. Relation between standard deviation and average durability factor, LG concretes.

is, the mean durability factors should have been clustered about a value somewhere near the mean of the population, and the standard deviations should have been grouped about the standard deviation of the population. But here the mean durability factors of the samples range from 30 to 109 and standard deviations from less than 1 to 28, with the low standard deviations clustered at the low and high ends of the durability scale.

It is apparent that, even making allowance for the large differences between supposedly identical specimens (which is familiar to all who work with concrete) (4, 8, 22, 23), either the laboratories did not make the same concrete, or their test methods did not produce the same answers, or both. Evidence on both of these points is examined in the next section.

The point to be made here is that there is no reason to suppose that the actual characteristics of concretes in the laboratory method that produced mean durability factors below 15 or above 95 were really so much less variable than those with durability factors in the middle of the range. If, in Figure 15, only the points for rapid air are considered and the range of mean durability factors represents actual differences in the specimens between laboratories, the points at the low durability end of the scale represent laboratories that used a test method or "yardstick" which was insensitive to the variations that existed. To carry the yardstick analogy further, the durability of these specimens was smaller than the smallest division on the yardstick used to measure them. By the same token, the durability for the specimens at the high end of the range was beyond the capacity of the measuring instrument and variations did not show up.

The wider standard deviation found with specimens in the middle range of durability appears, therefore, to be a natural characteristic of this kind of testing. Hence results from specimens which show a low or a high durability, with the corresponding low variation, are not therefore better or more reliable.

Figure 16 shows results from the same concrete with coefficient of variation plotted

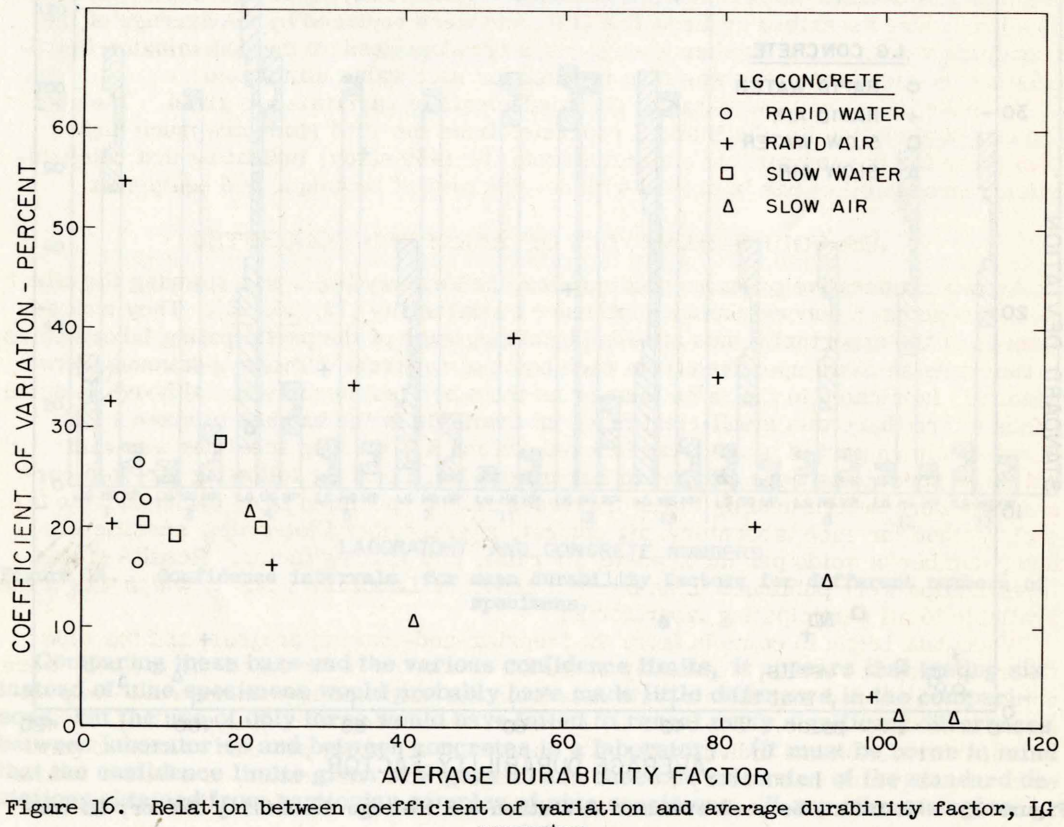

Figure 16. Relation between coefficient of variation and average durability factor, LG concretes.

against durability factor. The effect of plotting coefficient of variation instead of standard deviation is that the results at the low end of the range are raised. The curve still declines, however, to the high durability range.

COMPARISON OF VARIABILITY IN 1959 AND 1944 PROGRAMS

It is of interest to compare the reproducibility of results in the program under discussion and in the 1944 cooperative program (3). Concretes B and C of the 1944 program were made at the Bureau of Public Roads Laboratory and distributed to the other laboratories, where they were subjected to a uniform "coordinating" method of freezing and thawing. (Specimens were fabricated for other testing as well, but only those subjected to the uniform freezing-and-thawing test are considered here.) Variability (expressed as standard error of the mean) and coefficients of variation were determined for each concrete in each program and are presented in Table 10.

TABLE 10

VARIABILITY IN 1959 AND 1944 PROGRAMS[1]

Concrete	Test Method	Mean Durability Factor	Standard Error of Mean[2]	Coefficient of Variation[2]
LG (1959)	C 290	7	0.69	10.4
	C 291	37	1.97	5.2
	C 292	15	1.26	8.5
	C 310	73	2.20	2.9
HG (1959)	C 290	52	2.05	4.0
	C 291	98	1.47	1.5
	C 292	41	3.20	7.9
	C 310	106	0.57	0.5
HP (1959)	C 290	6	0.49	8.7
	C 291	10	1.26	12.0
	C 292	8	0.72	9.1
	C 310	13	2.03	15.1
B (1944)	Standard[3]	17	5.97	35.4
C (1944)	Standard[3]	2	0.59	30.3

[1]Results averaged over all laboratories.
[2]Variability obtained after elimination of outlying values.
[3]Standard method for 1944 program is the "coordinating" method set up for that program (3).

The standard errors given in Table 10 are an actual measure of how much means of the three batches in a given concrete differed among themselves for each test method, when outlying values (which were probably affected by some other influence than the mere batch-to-batch variation) were removed. These outlying values were eliminated by a procedure described by Proschan (12), and were replaced by the average of the remaining values. The number of degrees of freedom used as the denominator in calculating the standard error was then reduced for each value eliminated.

To make the values comparable, the coefficients of variation are given. The coefficients of variation for the B and C concretes from the 1944 study are much higher than those for the comparable concretes from the 1959 study, indicating that batch-to-batch reproducibility has improved with development of technique and equipment.

AIR-VOID PARAMETERS OF HARDENED CONCRETES

As this cooperative program was starting, Laboratory No. 1 was studying the effect of void spacing in concrete and its influence on durability (13, 14, 15). They took advantage of the opportunity thus afforded by asking each of the participating laboratories to fabricate an extra specimen from each batch of concrete. These specimens were generally fabricated in the same manner as the other test specimens, although in some cases where there was insufficient material available in the batches to make a full-sized specimen part of a mold was blocked out and a 6-in. long specimen was cast. All these specimens were shipped to Laboratory No. 1 and the following air-void parameters were determined by linear traverses on one specimen from each concrete for each method for each laboratory: air content, average chord intercept, specific surface, number of voids per inch, paste/air ratio, and spacing factor. Results of this investigation were published in an internal report of Laboratory No. 1, which was made available to all participating laboratories.

When data began to come in from the freezing-and-thawing program and the wide discrepancies in results, especially in the LG concretes in the rapid-air method, were noted, it was hoped that the air-void data from the hardened specimens would help explain these differences. The results, however, were somewhat disappointing. More recent information has indicated that the number of air voids per unit volume of paste or concrete (which Laboratory No. 1 was not equipped to determine) is a better indicator of the effectiveness of the air voids in producing frost resistance than other parameters and might be of more value in interpreting the freezing-and-thawing results. Therefore, the specimens were shipped to Laboratory No. 10, where all the previous air-void parameters were redetermined, and, from the distribution of the lengths of chord intercepts, the total number of air voids in a unit volume of the paste and concrete was calculated by the method suggested by Lord and Willis (16).

Figure 17 shows a comparison of air-void parameters determined by the two laboratories. Somewhat different values for air content and specific surface of air voids were obtained. However, the number of voids per inch of traverse, and particularly the calculated spacing factors, were similar. The air-void parameters used in the discussion to follow are those determined in this re-examination.

It should be pointed out that one single specimen (not one of those actually frozen) from each laboratory was taken as representative of all the batches prepared for one type of concrete in that laboratory. This does not represent an ideal situation for an analysis of the influence of air-void parameters on the durability. Therefore, some of the actual freezing-and-thawing specimens were examined in order to obtain specific

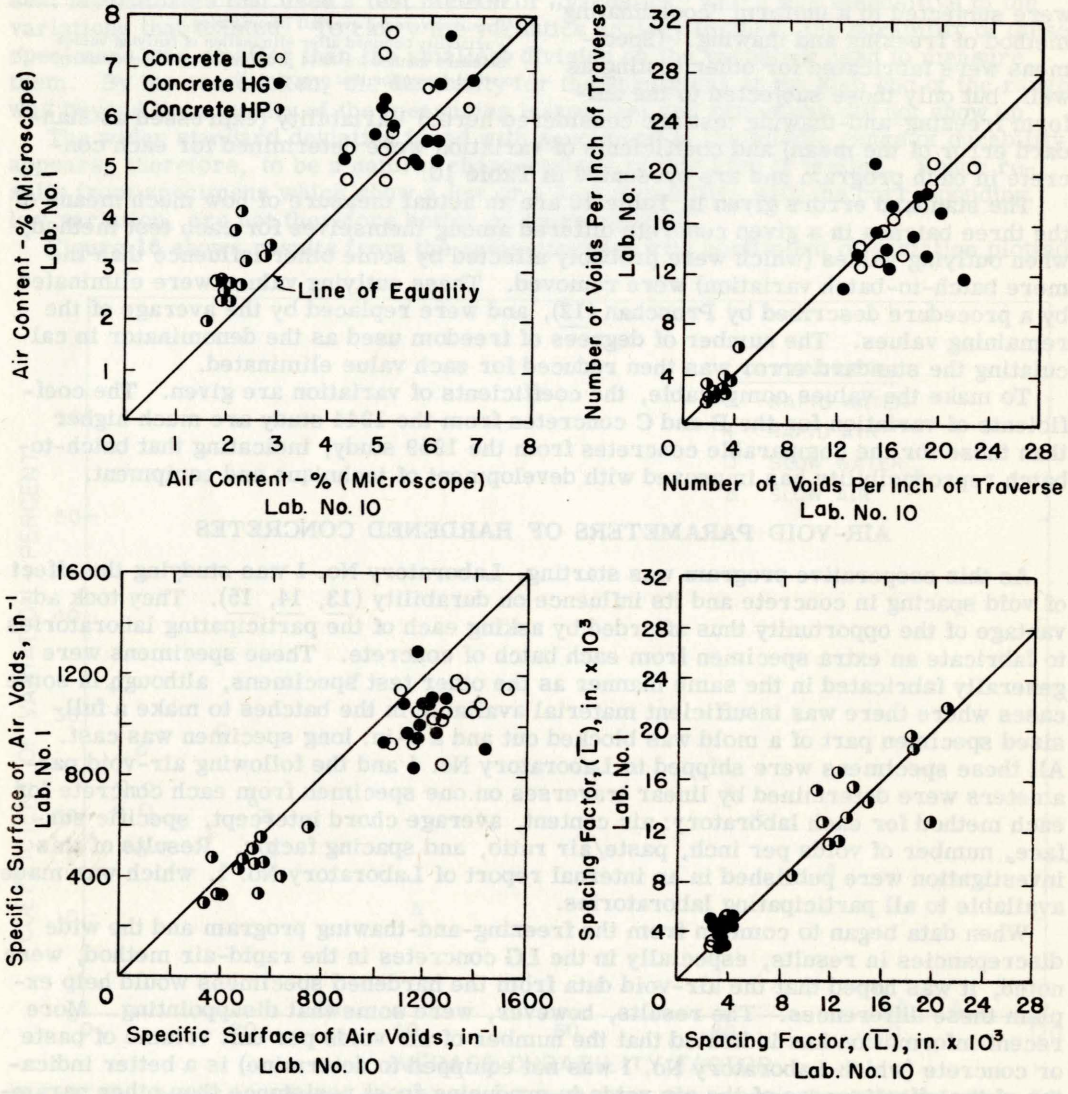

Figure 17. Comparison of air-void parameters as measured by two laboratories.

TABLE 11

AIR-VOID PARAMETERS OF HARDENED CONCRETES

Laboratory No.	Concrete	Average Air-Entraining Admixture (ml/bg)	Air Content (percent)		Void Parameters Determined by Microscope					
			Meter [1]	Microscope [2]	Number per Inch	Specific Surface, (in.$^{-1}$)	Paste/Air Ratio	Spacing Factor, L (in.)	Voids (no./10^{-6} cu in.) Concrete	Voids (no./10^{-6} cu in.) Paste
1	LG	7.0	2.6	2.14	3.4	635	11.62	0.0108	0.96	3.58
	HG	57.0	6.8	5.92	17.8	1,205	3.99	0.0033	5.71	19.99
	HP	50.9	7.1	5.29	15.2	1,150	4.61	0.0038	5.72	19.25
2	LG	5.4	2.7	1.80	1.8	400	13.86	0.0183	0.24	0.91
	HG	48.6	6.8	5.25	13.6	1,035	4.53	0.0042	3.58	12.33
	HP	41.0	7.0	5.11	13.7	1,065	4.79	0.0042	3.49	12.80
3	LG	10.0	2.9	2.38	3.1	520	10.42	0.0125	0.48	1.74
	HG	52.0	7.1	5.67	15.8	1,115	4.18	0.0037	4.89	16.65
	HP	43.0	7.0	4.35	13.9	1,280	5.66	0.0038	4.15	14.31
4	LG	4.9	2.9	2.26	4.2	745	10.99	0.0089	0.58	2.14
	HG	33.8	7.0	6.16	18.3	1,190	3.82	0.0032	6.09	20.50
	HP	33.8	6.4	6.73	18.5	1,100	3.57	0.0032	5.68	18.46
5	LG	9.8	2.6	1.62	2.3	570	15.43	0.0137	0.34	1.27
	HG	47.8	7.0	6.12	22.0	1,440	3.85	0.0027	9.24	31.13
	HP	45.3	6.4	5.09	17.1	1,345	4.80	0.0034	6.85	23.17
6	LG	12.1	3.0	2.78	3.7	530	8.89	0.0113	0.70	2.54
	HG	59.7	6.9	6.12	19.0	1,240	3.85	0.0031	7.01	23.60
	HP	61.1	6.5	5.08	15.9	1,250	4.81	0.0037	6.30	21.31
7	LG	7.8	2.7	1.87	1.7	365	13.34	0.0198	0.19	0.72
	HG	64.0	6.3	5.03	16.1	1,280	4.74	0.0036	6.98	24.18
	HP	62.8	6.3	5.90	19.3	1,310	4.11	0.0031	7.66	25.43
8	LG	6.5	2.9	1.94	1.9	390	12.85	0.0182	0.22	0.82
	HG	31.6	6.4	4.30	12.4	1,155	5.59	0.0043	4.48	15.81
	HP	32.6	6.6	5.20	16.4	1,260	4.70	0.0036	4.49	15.15
9	LG	9.8	2.2	2.30	3.2	555	10.80	0.0119	0.74	2.74
	HG	43.2	6.5	5.09	14.9	1,170	4.68	0.0039	5.42	18.74
	HP	44.9	6.3	5.09	19.3	1,515	4.80	0.0030	8.23	27.87
10	LG	6.5	2.8	1.89	2.3	485	13.19	0.0149	0.26	0.98
	HG	37.5	6.8	4.90	15.0	1,225	4.87	0.0037	5.40	18.77
	HP	41.9	6.7	4.40	15.5	1,410	5.60	0.0034	5.80	19.99
11	LG	7.2	2.6	2.04	1.7	335	12.20	0.0210	0.10	0.40
	HG	54.0	6.8	5.74	16.1	1,120	4.12	0.0036	4.34	14.76
	HP	65.6	6.4	5.42	18.7	1,380	4.50	0.0032	6.82	22.89
12	LG	6.5	2.9	2.85	3.3	465	8.66	0.0131	0.38	1.37
	HG	46.5	7.0	6.81	20.0	1,175	3.44	0.0030	6.37	21.08
	HP	61.2	6.8	6.02	18.6	1,235	4.02	0.0032	6.30	20.85
13	LG	10.4	2.7	2.13	2.9	545	11.68	0.0125	0.48	1.78
	HG	41.3	6.8	6.44	18.9	1,175	3.65	0.0032	5.23	17.47
	HP	44.5	6.0	7.75	22.6	1,165	3.07	0.0027	6.30	19.98

[1] Average of all batches for each type of concrete.
[2] Determination on one specimen representing each type of concrete.

information for the same specimens used in the tests. Only a few of these actual freezing-and-thawing specimens were still available for this purpose.

Table 11 shows the air-void parameters determined by Laboratory 10 on the single specimen supposedly representative of each type of concrete from each laboratory. The amount of air-entraining admixture was varied by the individual laboratories as required to provide an air content within the range specified for the particular concrete. These air contents were measured by the pressure method. The amounts of air-entraining admixture required to produce a given air content varied due to differences in mixer characteristics, concrete temperatures, differences in slump, and other possible variables. Air-void parameters such as specific surface, spacing factor, and number of voids, varied among the different laboratories. In this connection, a separate series of tests conducted by Laboratory No. 1, and described in the previously mentioned internal report, indicated that differences in compaction had little effect on spacing factor and number of voids per inch of traverse, but could influence the volume of air present in both the freshly mixed and hardened concretes. This indicates that compaction may remove some of the large air voids that account for a significant volume of air but leave relatively undisturbed the minute air voids which are important from the standpoint of frost resistance (17).

For all concretes, the general trends established show that increases in the amount

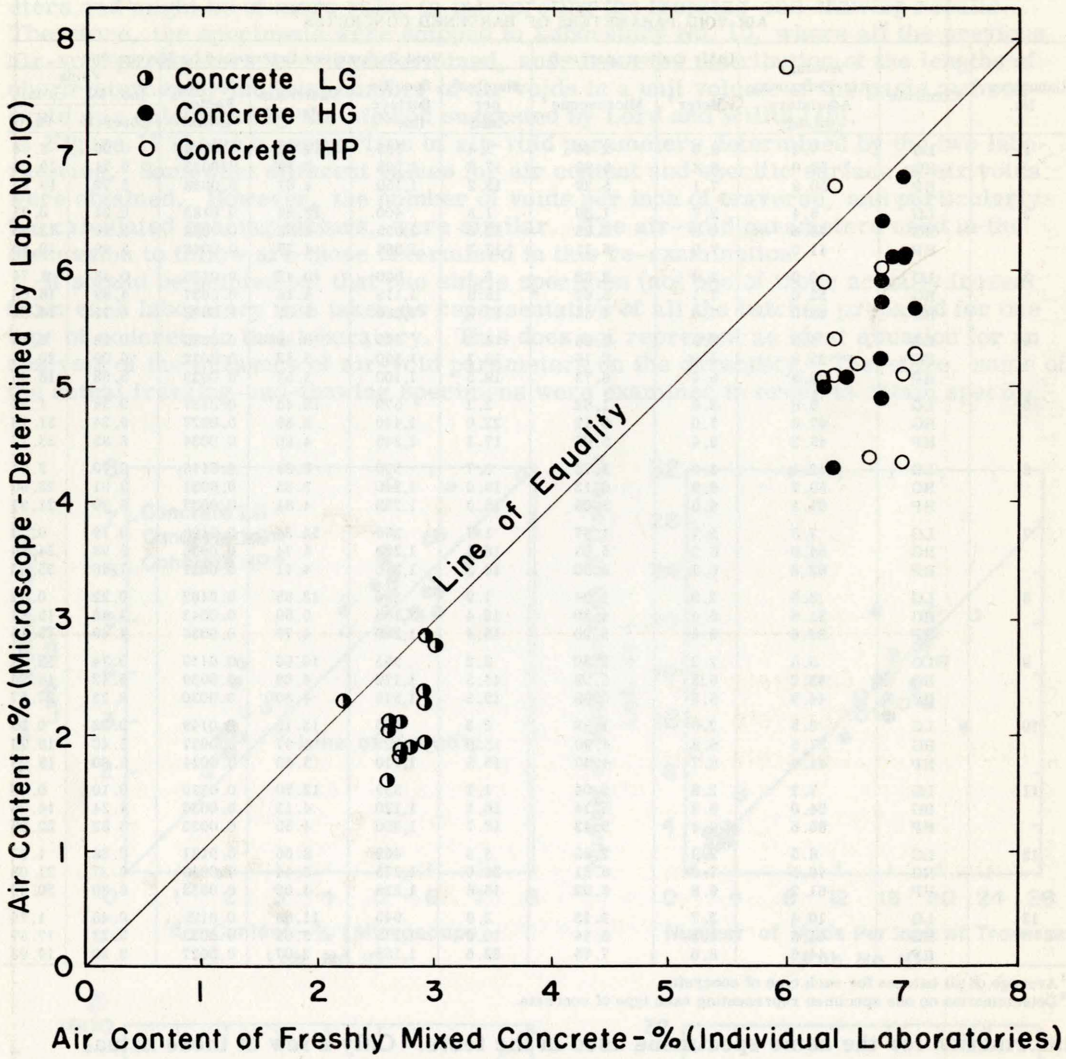

Figure 18. Comparison of air contents of freshly mixed and hardened concretes.

of air-entraining admixture resulted in increases in air content (of both the freshly mixed and hardened concretes), specific surface, number of voids per inch of traverse, and number of voids per unit volume; and in decrease in the spacing factors of the hardened concrete. These were not well-defined relationships due to the influence of mixer characteristics, slump, temperature, etc.

Although it was realized that controlling the volume of air entrained at the time of mixing would not necessarily control the other air-void parameters, this was the only feasible means of attempting the control of air-void characteristics. Figure 18 shows that the microscopically-determined air contents did not correlate well with the air contents of the freshly mixed concretes. The air contents determined by microscope were generally lower than those determined by the pressure method on the freshly mixed concrete, these differences ranging from 0.1 to 2.6 percent of air. All subsequent references to air content are to the volume of air in the hardened concrete specimens.

Figure 19 shows the relationships between air content and both specific surface and calculated spacing factor. Neither relationship is well defined, particularly the one

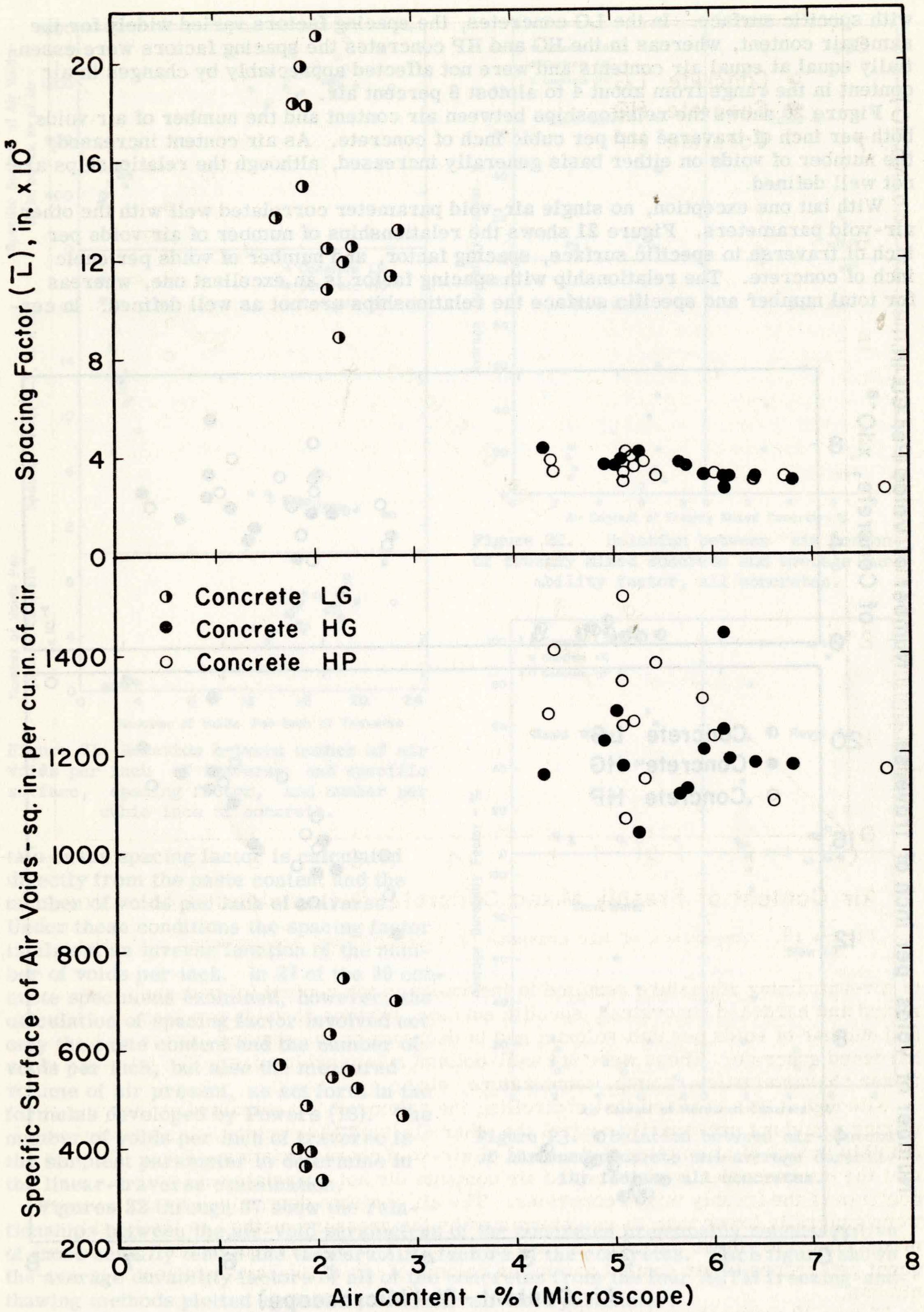

Figure 19. Relation between air content of hardened concrete and specific surface and spacing factor of air voids.

with specific surface. In the LG concretes, the spacing factors varied widely for the same air content, whereas in the HG and HP concretes the spacing factors were essentially equal at equal air contents and were not affected appreciably by changes in air content in the range from about 4 to almost 8 percent air.

Figure 20 shows the relationships between air content and the number of air voids, both per inch of traverse and per cubic inch of concrete. As air content increased, the number of voids on either basis generally increased, although the relationships are not well defined.

With but one exception, no single air-void parameter correlated well with the other air-void parameters. Figure 21 shows the relationships of number of air voids per inch of traverse to specific surface, spacing factor, and number of voids per cubic inch of concrete. The relationship with spacing factor is an excellent one, whereas for total number and specific surface the relationships are not as well defined. In certain cases spacing factor is calculated directly from the paste content and the number of voids per inch of traverse. Under these conditions the spacing factor is almost an inverse function of the number of voids per inch. In 27 of the 39 concrete specimens examined, however, the calculation of spacing factor involved not only the paste content and the number of voids per inch, but also the measured volume of air present, as set forth in the formulas developed by Powers (18). The number of voids per inch of traverse is the simplest parameter to determine in the linear-traverse examination.

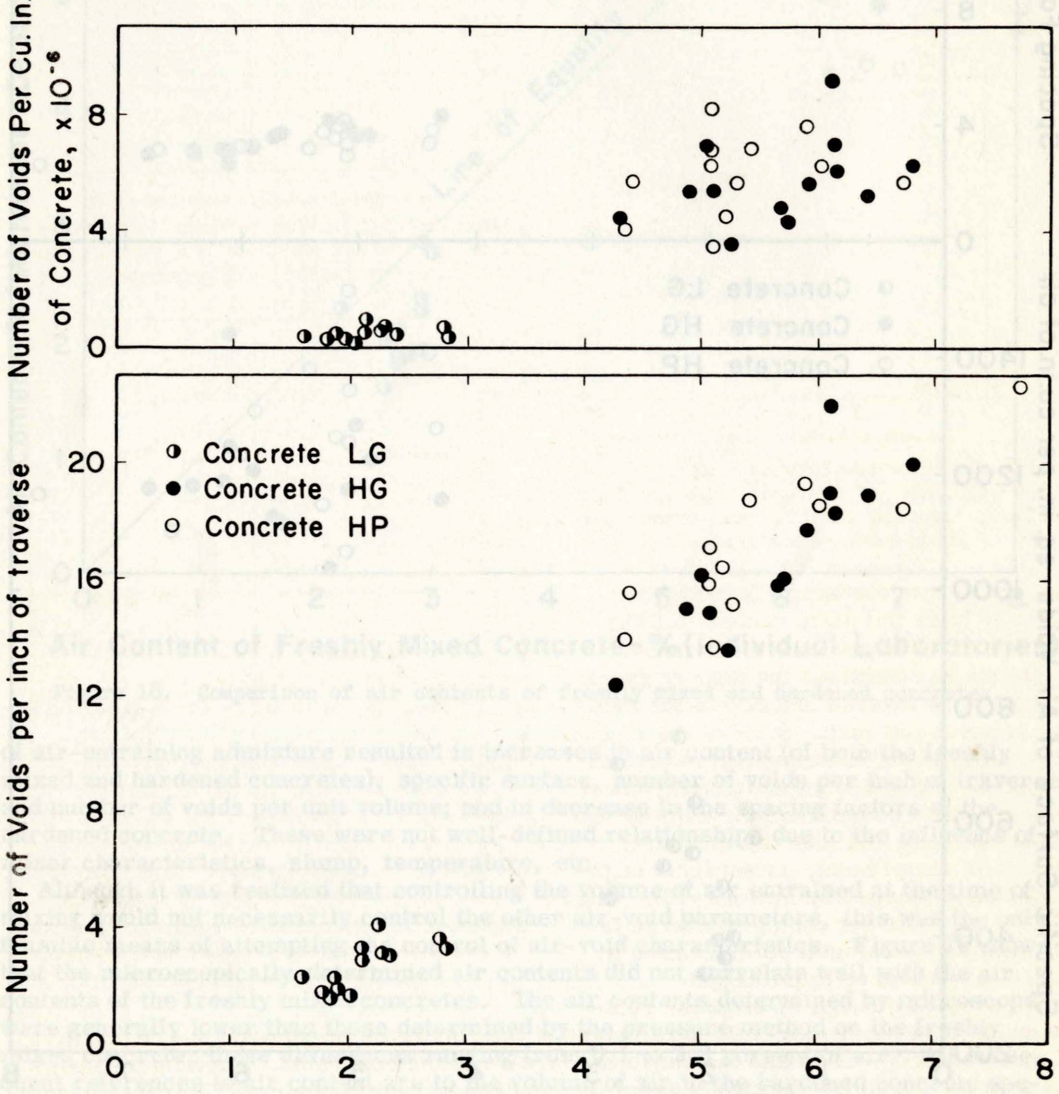

Figure 20. Relation between air content of hardened concretes and number of air voids per inch of traverse and per cubic inch of concrete.

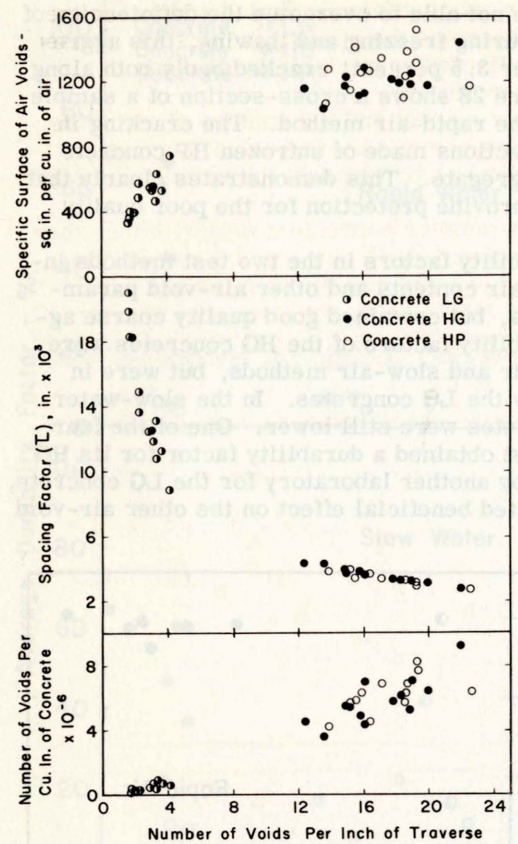

Figure 21. Relation between number of air voids per inch of traverse and specific surface, spacing factor, and number per cubic inch of concrete.

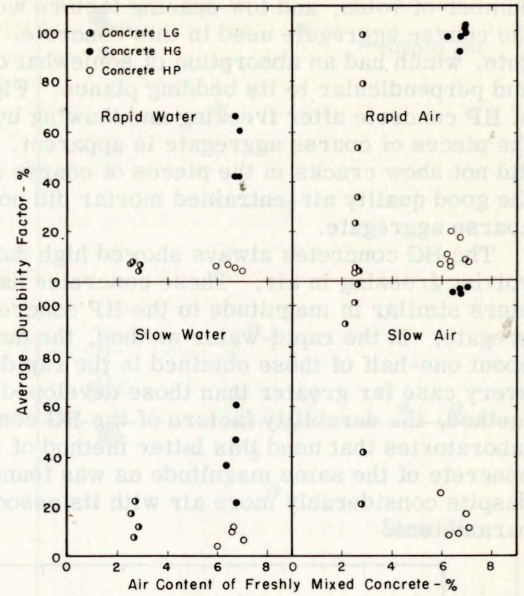

Figure 22. Relation between air content of freshly mixed concrete and average durability factor, all concretes.

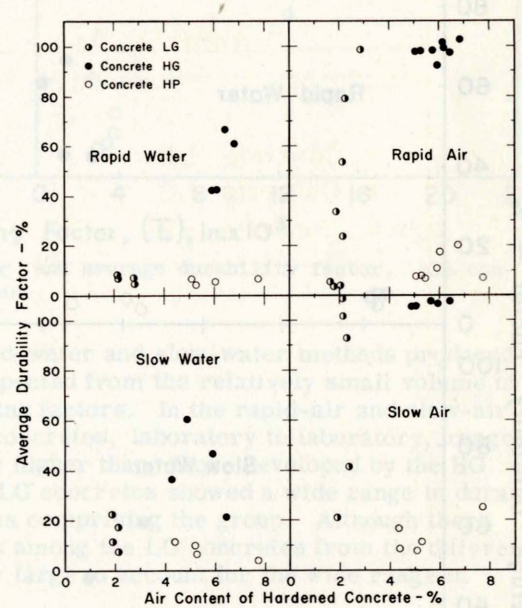

Figure 23. Relation between air content of hardened concrete and average durability factor, all concretes.

Figures 22 through 27 show the relationships between the air-void parameters of the concretes presumably representative of those actually tested and the durability factors of the concretes. Each figure shows the average durability factors of all of the concretes from the four ASTM freezing-and-thawing methods plotted against a particular air-void parameter.

It is apparent that the low durability of the HP concretes was not due to deficiencies in the air-void system. High air contents and their associated high specific surfaces, number of voids, and low spacing factors were not able to overcome the deficiencies of the coarse aggregate used in this concrete. During freezing and thawing, this aggregate, which had an absorption of somewhat over 3.5 percent, cracked badly both along and perpendicular to its bedding planes. Figure 28 shows a cross-section of a sample of HP concrete after freezing and thawing by the rapid-air method. The cracking in the pieces of coarse aggregate is apparent. Sections made of unfrozen HP concrete did not show cracks in the pieces of coarse aggregate. This demonstrates clearly that the good quality air-entrained mortar did not provide protection for the poor quality coarse aggregate.

The HG concretes always showed high durability factors in the two test methods involving freezing in air. These concretes had air contents and other air-void parameters similar in magnitude to the HP concretes, but contained good quality coarse aggregate. In the rapid-water method, the durability factors of the HG concretes were about one-half of those obtained in the rapid-air and slow-air methods, but were in every case far greater than those developed by the LG concretes. In the slow-water method, the durability factors of the HG concretes were still lower. One of the four laboratories that used this latter method of test obtained a durability factor for its HG concrete of the same magnitude as was found by another laboratory for the LG concrete, despite considerably more air with its associated beneficial effect on the other air-void parameters.

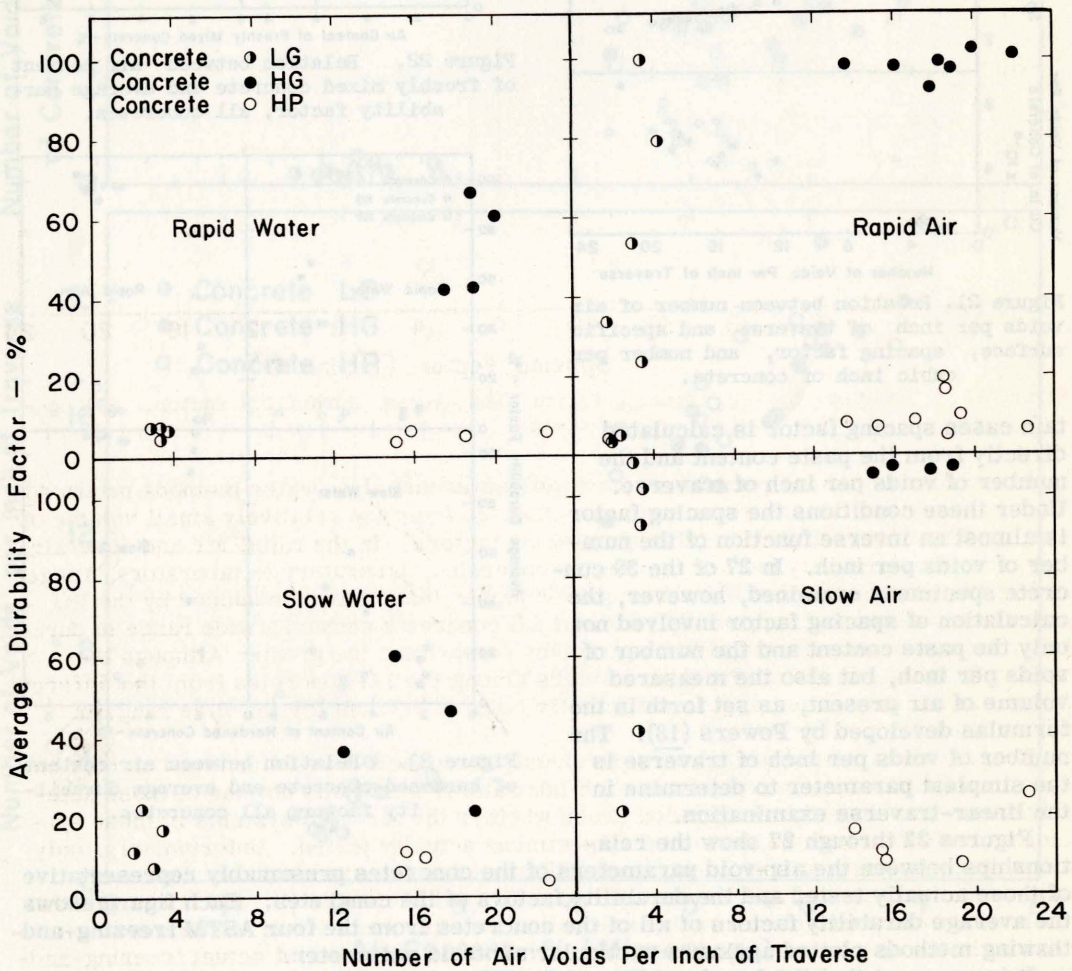

Figure 24. Relation between number of voids per inch of traverse and average durability factor, all concretes.

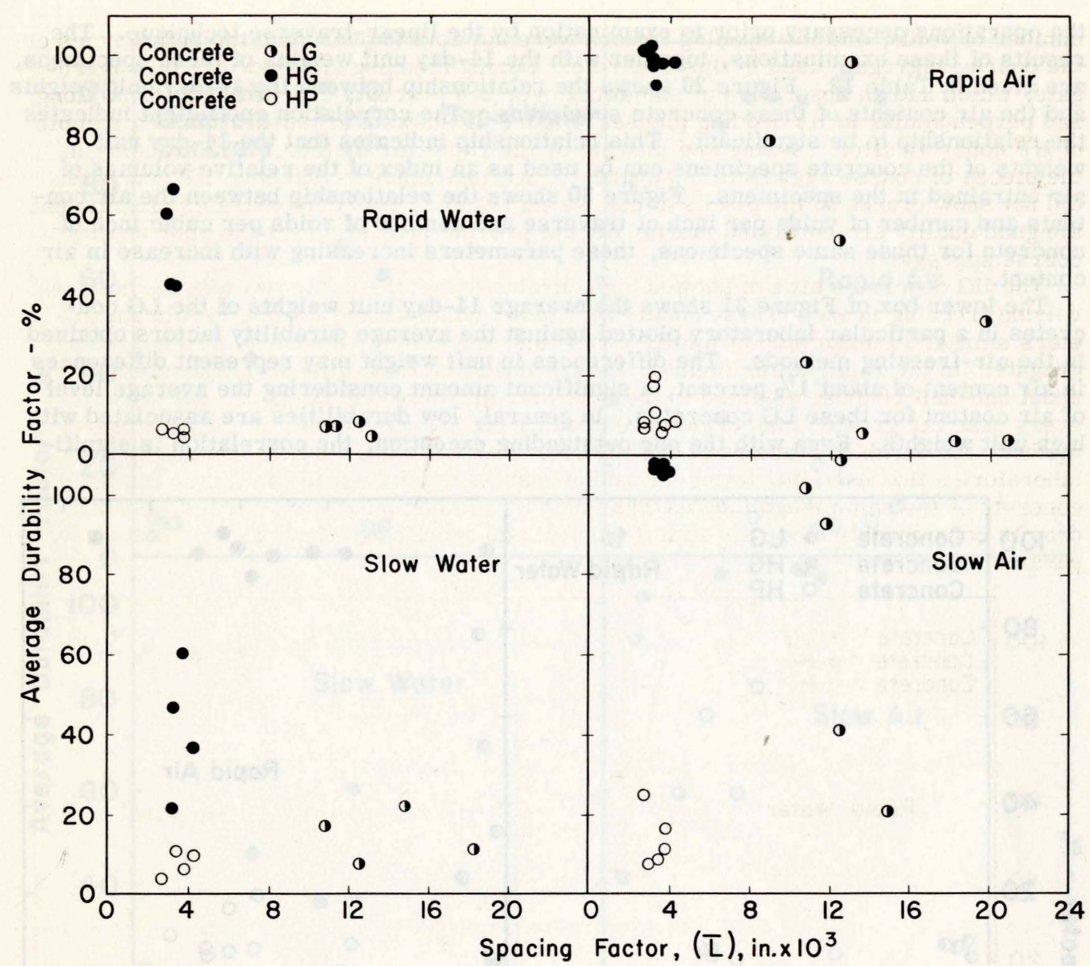

Figure 25. Relation between spacing factor and average durability factor, all concretes.

In the case of the LG concretes, the rapid-water and slow-water methods produced the low durability factors which would be expected from the relatively small volume of air, small number of voids, and large spacing factors. In the rapid-air and slow-air methods, the durability factors for the LG concretes, laboratory to laboratory, ranged widely from extremely low to as high as, or higher than, those developed by the HG concretes. Groups of supposedly identical LG concretes showed a wide range in durability factors among the individual specimens comprising the group. Although there were differences in the air-void parameters among the LG concretes from the different laboratories, they do not appear sufficiently large to account for the wide range in durabilities.

Because the air-void parameters previously discussed were determined on only one specimen (from each concrete from each laboratory) which was not one of those actually frozen and thawed, the question arose whether the air-void systems in these specimens truly represented those in the specimens actually tested. Unfortunately, only a few of the actual test specimens were still available for examination. However, unit-weight data for all specimens had been reported (Appendix E), and it was felt that variations in unit weight should to some extent be representative of variations in air content in the specimens. To check this assumption, a number of actual freezing-and-thawing specimens of LG concretes were shipped to Laboratory No. 10 by two of the participating laboratories. Of these, 26 were sufficiently intact to enable performing the operations necessary prior to examination by the linear-traverse technique. The results of these examinations, together with the 14-day unit weights of these specimens, are given in Table 12. Figure 29 shows the relationship between the 14-day unit weights and the air contents of these concrete specimens. The correlation coefficient indicates the relationship to be significant. This relationship indicates that the 14-day unit weights of the concrete specimens can be used as an index of the relative volumes of air entrained in the specimens. Figure 30 shows the relationship between the air contents and number of voids per inch of traverse and number of voids per cubic inch of concrete for these same specimens, these parameters increasing with increase in air content.

The lower box of Figure 31 shows the average 14-day unit weights of the LG concretes in a particular laboratory plotted against the average durability factors obtained in the air-freezing methods. The differences in unit weight may represent differences in air content of about 1½ percent, a significant amount considering the average level of air content for these LG concretes. In general, low durabilities are associated with high unit weights. Even with the one outstanding exception, the correlation is signifi-

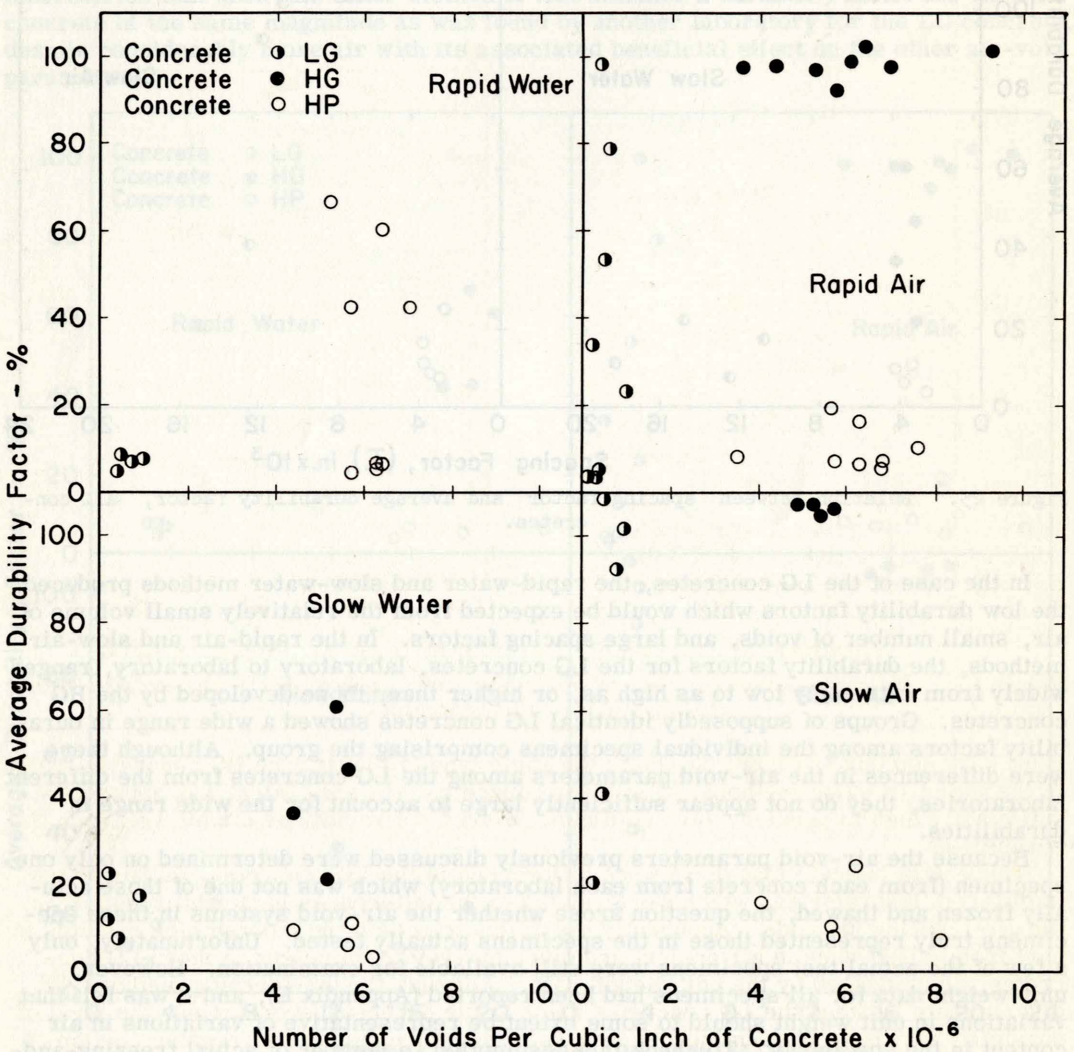

Figure 26. Relation between number of voids per cubic inch of concrete and average durability factor, all concretes.

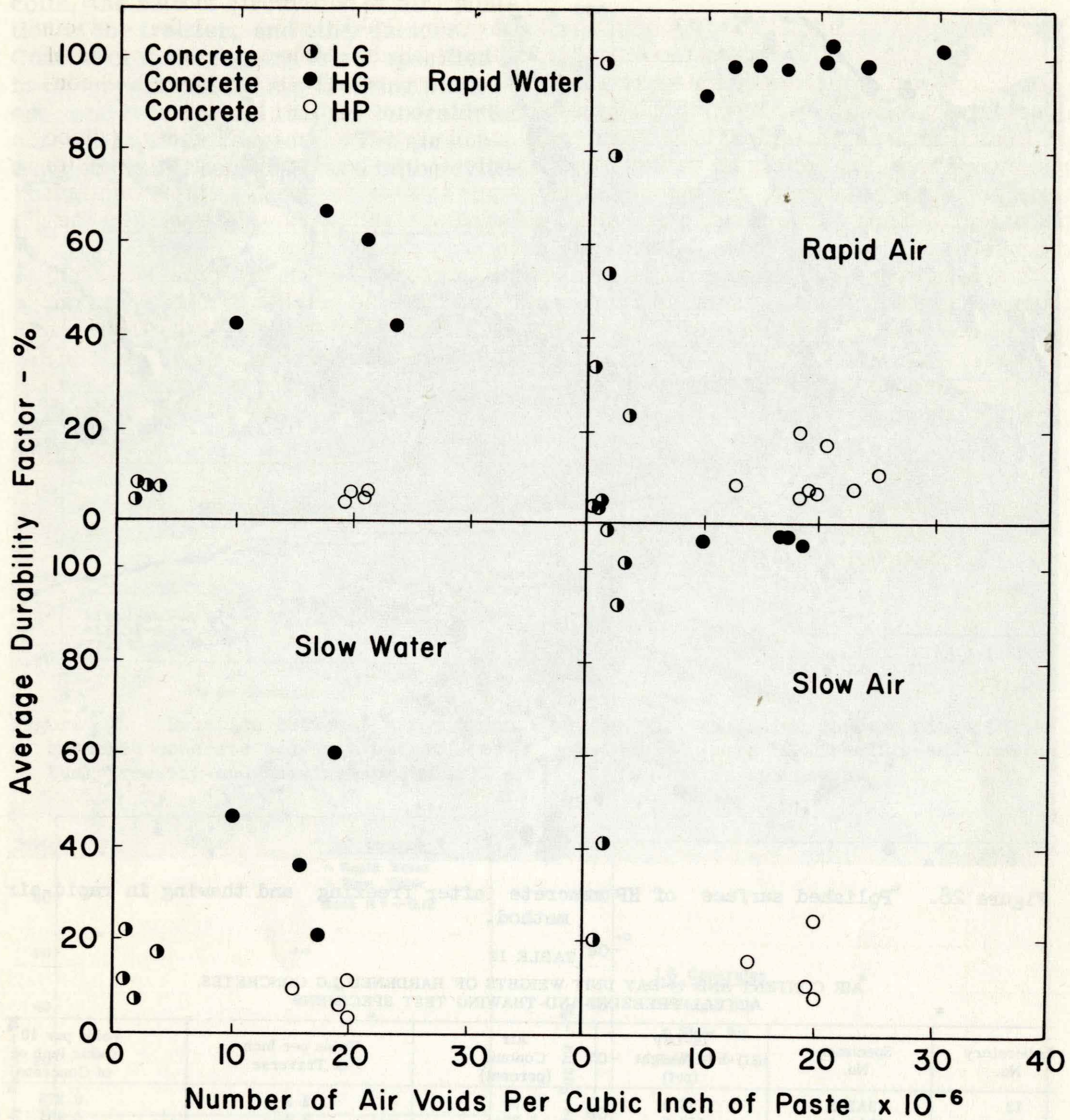

Figure 27. Relation between number of voids per cubic inch of paste and average durability factor, all concretes.

cant. The top box of Figure 31 shows the same type of plot for the HG concretes tested in the water-freezing methods. For these concretes, the air content was apparently sufficiently high to preclude any significant influence of variations in unit weight on the durabilities.

These data indicate that there were differences in the LG concretes, as fabricated in different laboratories, which were related to the differences in durability factor in the air-freezing methods. Apparently the differences between laboratories resulted in part from differences in air content and other air-void parameters in these LG concretes, as evidenced by the unit-weight data. Although the air-freezing methods did discriminate between the LG concretes made in the different laboratories, the level of durability may have been influenced by loss of moisture during the freezing portion of the cycle. Freezing of moist concrete by air may result in loss of moisture. The amount of moisture loss which may occur will depend on the temperature of the cooling

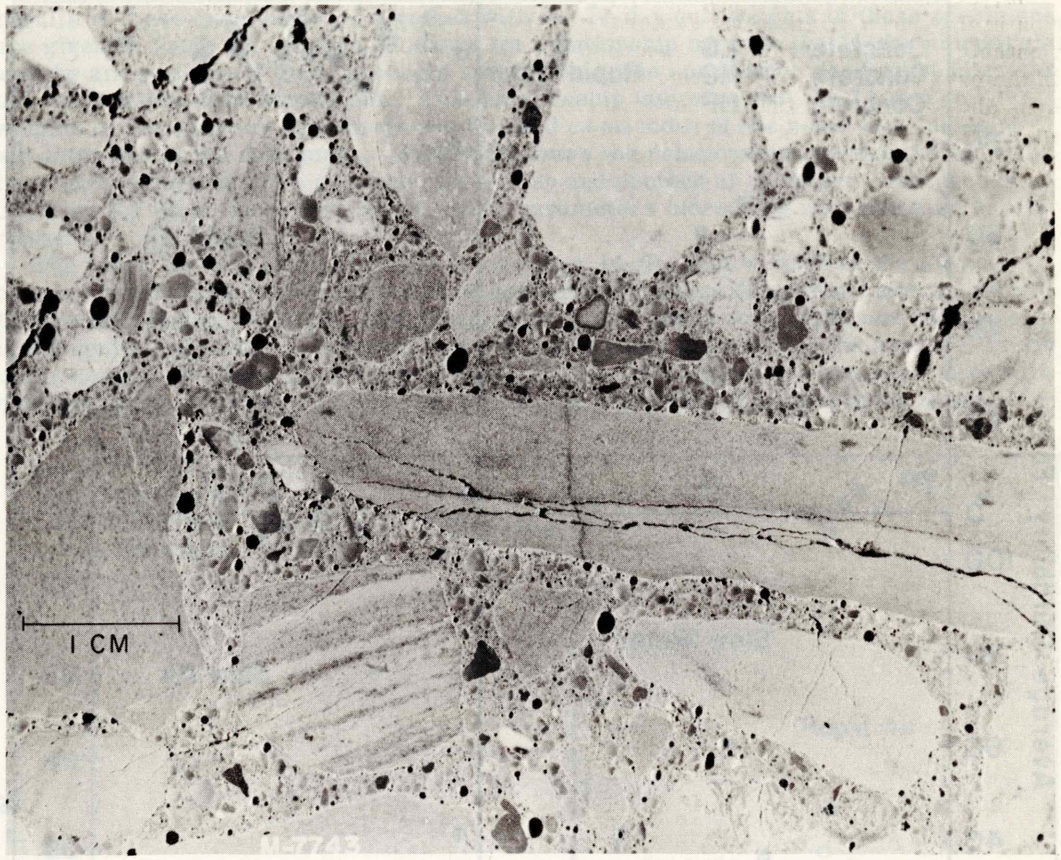

Figure 28. Polished surface of HP concrete after freezing and thawing in rapid-air method.

TABLE 12

AIR CONTENT AND 14-DAY UNIT WEIGHTS OF HARDENED LG CONCRETES. ACTUAL FREEZING-AND-THAWING TEST SPECIMENS

Laboratory No.	Specimen No.	14-Day Unit Weight (pcf)	Air Content (percent)	Voids per Inch of Traverse	Voids per 10^{-6} Cubic Inch of of Concrete
13 Rapid-air	13A2-3	150.4	2.09	2.3	0.278
	13A4-1	149.6	3.27	3.4	0.461
	13A5-2	149.8	2.48	2.8	0.254
	13A6-3	149.7	2.54	3.2	0.281
	13A8-1	149.1	3.09	3.4	0.398
	13A9-2	149.6	3.06	3.2	0.340
	13A10-3	149.5	3.24	3.8	0.440
	13A12-1	149.9	3.03	3.5	0.380
13 Slow-air	13A2-1R	150.6	2.65	3.2	0.357
	13A3-2	149.6	3.16	3.2	0.280
	13A4-3	149.8	2.85	3.0	0.403
	13A6-1	149.8	2.77	3.3	0.485
	13A7-2	149.9	2.89	3.3	0.347
	13A8-3	149.0	2.75	3.5	0.387
	13A10-1	149.7	2.25	3.8	0.534
	13A11-2	149.4	2.58	3.3	0.378
	13A12-3	149.4	3.03	3.4	0.562
1 Slow-air	SAA1-1	150.8	2.18	1.7	0.090
	SAA1-2	151.6	2.21	1.4	0.087
	SAA1-3	151.7	1.92	1.5	0.104
	SAA2-1	150.9	2.15	1.9	0.173
	SAA2-2	150.8	1.68	1.4	0.117
	SAA2-3	151.0	1.32	1.2	0.106
	SAA3-1	150.8	2.05	1.5	0.155
	SAA3-2	150.7	1.72	1.4	0.062
	SAA3-3	150.8	2.20	1.7	0.153

coils, the rate of circulation of air, position in the freezer, and other factors. Control of these factors is not specified in the present ASTM air-freezing methods, and it is certain that the laboratories differed in these respects. The air contents of the LG concretes are in the criti-

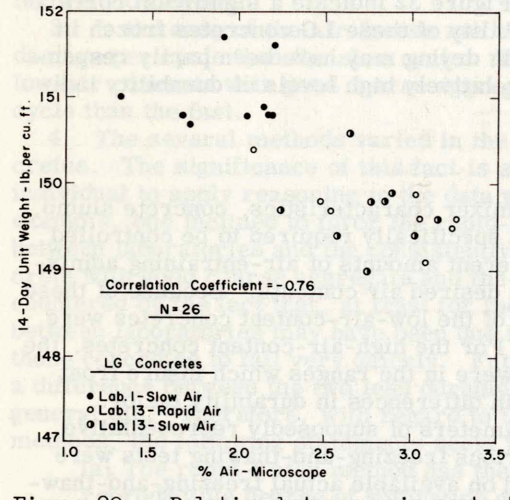

Figure 29. Relation between air content of hardened concrete and unit weight (actual freezing-and-thawing specimens).

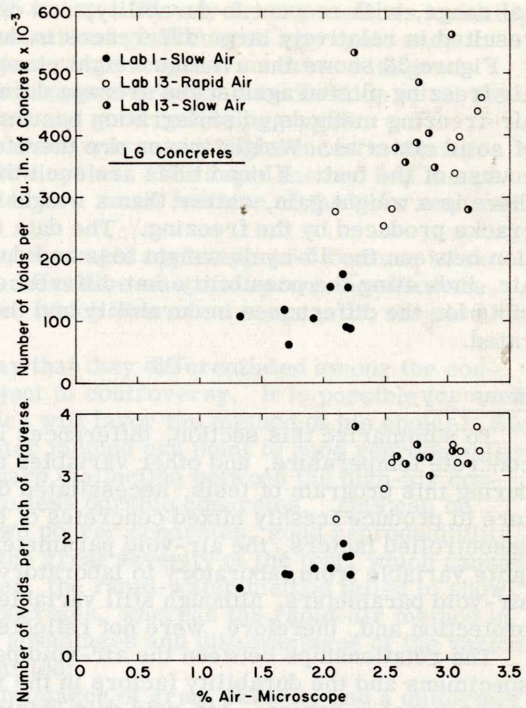

Figure 30. Relation between air-void parameters of some LG freezing-and-thawing specimens.

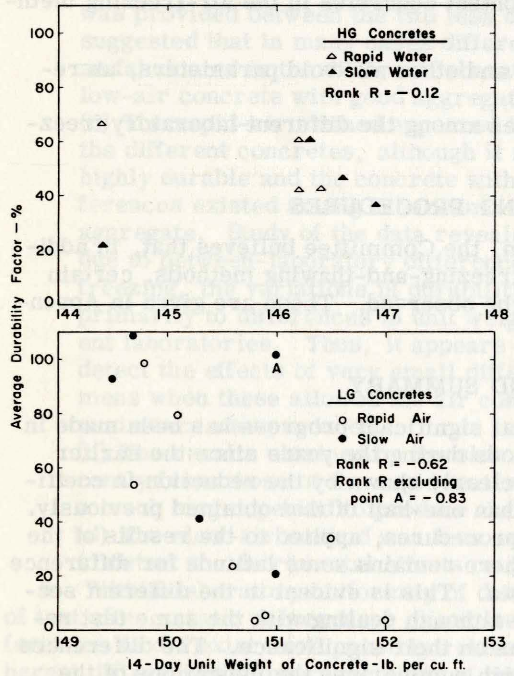

Figure 31. Relation between unit weight and average durability factor in individual laboratories.

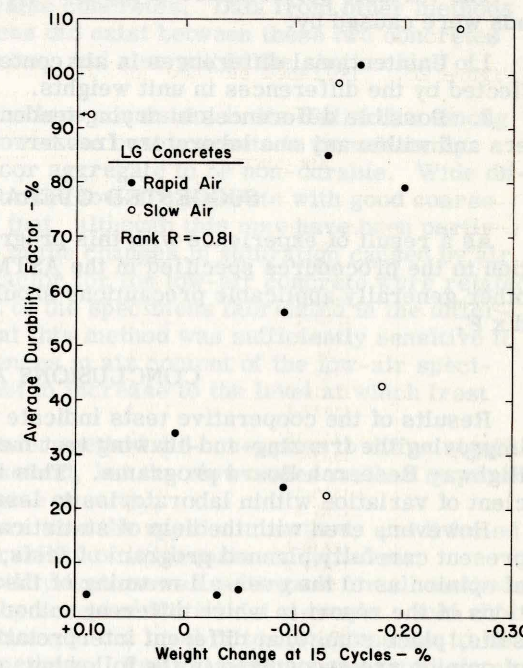

Figure 32. Relation between weight change during freezing and average durability factor, individual laboratories.

cal range, with respect to durability, and differences in drying in this case may have resulted in relatively large differences in durability factor.

Figure 32 shows the average weight changes of the LG concretes after 15 cycles of air freezing plotted against the average durability factors of these concretes. In the air-freezing methods, disintegration occurs by internal cracking rather than by loss of solid material. Weight losses are therefore indicative of moisture loss during the course of the test. If conditions are such that the concrete deteriorates in a few cycles, there is a weight gain, rather than a weight loss, due to entrance of water into the cracks produced by the freezing. The data in Figure 32 indicate a significant correlation between the 15-cycle weight loss and durability of these LG concretes frozen in air, indicating the possibility that differences in drying may have been partly responsible for the differences in durability and the relatively high levels of durability indicated.

Summary

To summarize this section, differences in mixer characteristics, concrete slump, concrete temperature, and other variables not specifically required to be controlled during this program of tests, necessitated different amounts of air-entraining admixture to produce freshly mixed concretes of the desired air contents. Because of these uncontrolled factors, the air-void parameters of the low-air-content concretes were quite variable from laboratory to laboratory. For the high-air-content concretes, the air-void parameters, although still variable, were in the ranges which insure frost protection and, therefore, were not reflected in differences in durability factor.

The relationships between the air-void parameters of supposedly representative specimens and the durability factors in the various freezing-and-thawing tests were only general in nature. Air-void data obtained on available actual freezing-and-thawing specimens showed a significant correlation with unit weight of the specimens. There was a significant correlation between unit weight of the LG concretes and the durability factors obtained in the air-freezing methods.

The variable performance of the low-air-content concretes in the air-freezing methods were caused by:

1. Unintentional differences in air content and other air-void parameters, as reflected by the differences in unit weights.

2. Possible differences in drying tendencies among the different laboratory freezers and within any one laboratory freezer.

SUGGESTED OPERATING PROCEDURES

As a result of experience with this program, the Committee believes that, in addition to the procedures specified in the ASTM freezing-and-thawing methods, certain other generally applicable precautions should be observed. These are given in Appendix F.

CONCLUSIONS AND SUMMARY

Results of the cooperative tests indicate that significant progress has been made in improving the freezing-and-thawing test methods during the years since the earlier Highway Research Board programs. This is clearly shown by the reduction in coefficient of variation within laboratories to less than one-half of that obtained previously.

However, even with the help of statistical procedures, applied to the results of the present carefully planned program of tests, there remains some latitude for difference of opinion as to the over-all meaning of the data. This is evident in the different sections of the report in which different authors, although dealing with the same test results, place somewhat different interpretations on their significance. The differences of opinion are recognized in the following, which summarizes the indications of the tests:

1. The methods involving freezing and thawing in water were more severe than those involving freezing in air and thawing in water. The air-freeze methods had little or no effect on the concrete with high air content and good coarse aggregate and, in some cases, caused no serious damage to the low-air-content concrete with good coarse aggregate. The water-freeze methods caused greater deterioration of all the concretes, including that with high air content and good coarse aggregate.

2. For the water-freeze methods, there were only minor differences in damage produced per cycle between the rapid and slow cycles. The rapid method has the advantage of producing a given number of cycles in a small fraction of the time required for the slow cycle.

3. In the case of the air-freeze methods, the rapid cycle appears to cause more damage per cycle than the slow cycle. The difference was most pronounced for the low-air concrete with good coarse aggregate, which was more resistant to the slow cycle than the fast.

4. The several methods varied in the way that they differentiated among the concretes. The significance of this fact is subject to controversy. It is possible for each individual to apply reasoning to the data which will favor the method of his choice. For example, one inclined to favor the rapid-water method can point to good reproducibility between laboratories and the consistently sharp distinction between the high-air concrete with good coarse aggregate and the two less durable concretes. This can be countered by the fact that, at least for the two poorer concretes, good reproducibility between laboratories may have been due to the great severity of the test, which caused those concretes to fail very quickly. Further, the rapid-water method failed to show a difference between the two less durable concretes, whereas the rapid-air method in general did. Therefore, with regard to the advantages and disadvantages of the various methods, the following statements seem justified:

(a) The rapid-water method has the advantages of great severity and a uniformly reproducible degree of saturation during exposure. It distinguished quickly and decisively between very good concrete and concrete which was less durable either because of insufficient air or because of poor coarse aggregate. On the other hand, the severity of this method was apparently so great that no differentiation was provided between the two less durable concretes. Data from other methods suggested that in many cases differences did exist between these two concretes as fabricated in the different laboratories, and also within the single class of low-air concrete with good aggregate.

(b) The rapid-air method appeared to be less consistent in its distinction among the different concretes, although it showed the best concrete to be uniformly highly durable and the concrete with poor aggregate to be non-durable. Wide differences existed among laboratories for the low-air concrete with good coarse aggregate. Study of the data revealed that, although this may have been partly due to between-laboratory differences in the changes in saturation caused by air freezing, the variations in durability factor for the low-air concrete were related primarily to differences in unit weight of the specimens fabricated in the different laboratories. Thus, it appears that this method was sufficiently sensitive to detect the effects of very small differences in air content of the low-air specimens when these allowed the air content to increase to the level at which frost resistance was produced.

(c) The results obtained by the slow-water method did not appear to differ significantly from those of the rapid-water method, but the slow-water method required a much longer period to produce the same results.

(d) The slow-air method was less severe than the rapid-air method, and it failed to detect the detrimental effects on durability of inadequate entrained air.

5. Within-laboratory uniformity of durability factors was quite good for all methods of test after erratic values were eliminated by accepted statistical methods. Such differences as did exist were possibly related more to the level of test results than to inherent differences in reproducibility of the methods. For example, in the rapid-water cycle, reproducibility was excellent for the two poorer concretes because of their very rapid failure but was relatively less good for the good concrete, which produced intermediate durability factors. Poorer reproducibility of results in the middle range of

durability appears to be a natural and inescapable characteristic of results of this kind of testing.

6. Although an effort was made to control the air content of the freshly mixed concrete, there were significant differences in the hardened specimens, as evidenced by microscope measurements of air voids in the hardened concrete and observed variations in unit weight for the low-air concrete. These differences apparently accounted, at least partially, for the poor laboratory-to-laboratory uniformity of durability factors for this concrete in the air-freeze methods. At the high level of air content maintained in the other two concretes, observed differences of the same magnitude had no discernible effect on durability. It appears that, unless air itself is a variable under study, the uniformity of freezing-and-thawing tests can be improved by maintaining a moderately high air content, the level depending on the maximum size of the aggregate in the concrete.

7. With these concretes, six to nine specimens per concrete for each method in each laboratory were adequate to make comparisons, but three specimens would probably have been too few.

8. To increase the usefulness of laboratory freezing-and-thawing tests, additional research is needed on the degree to which they indicate field performance. Until more data on this aspect of the problem are available, it is not possible to recommend a specific test method. The more severe methods may cause failure of some concretes that would perform well under most field conditions. On the other hand, the less severe test methods may fail to cause deterioration of some concretes that would be vulnerable to severe field conditions. Another important consideration is that weathering conditions in the field range from highly destructive to completely innocuous and that differences shown by laboratory tests will in many cases have no practical significance. It seems likely that ability of a concrete to withstand a severe laboratory freezing-and-thawing test is evidence of a high degree of durability. Failure provides a warning that can aid in evaluating the need for altering the characteristics of the concrete.

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Appendix A

Significance of Differences Between Means

CONFIDENCE-LIMIT CURVES

On the confidence-interval curves (Figs. 5 through 8) it seems logical to assume that the test has discriminated between the concretes at the point where the upper confidence limit for the concrete of lower durability crosses the lower confidence limit for the concrete of higher durability. For example, in the slow-water method (Fig. 7), Laboratory No. 1, HG and LG concretes, this crossing occurred at about 30 cycles.

This, however, is a conservative estimate of the point of discrimination. The 95 percent confidence limit signifies that there is a 0.025 chance of the true mean for the upper group lying below its lower confidence limit, and a 0.025 chance of the true mean for the lower group lying above its upper confidence limit. The probability that the two confidence intervals will not overlap, when, in fact, the means are equal, is much less than 0.05. To calculate the exact probability is not easy except when the true standard deviations of the two populations are known. (Probability levels (single-tailed) for a significant difference between means were estimated for this crossing for the seven cases listed in Table 13, and the estimates varied from approximately 0.5 percent to 2 percent.)

To investigate the question of where a significant difference could be assumed and the test terminated with a reasonable assurance of being right, a statistical test for differences between means was applied to the curves at a number of points. (The calculation, use, and interpretation of statistical parameters such as mean and standard deviation are based, usually, on the assumption that the data under consideration are from normally-distributed populations. The durability factor is not a normally-distributed variable, because, for 60 percent relative E and 300 cycles as was used here, it is calculated differently for specimens which fail in 300 cycles or less than for those which run to 300 cycles without reaching 60 percent relative E. However, the distribution of averages of samples of n values rapidly approaches normality as n increases, regardless of the shape of the underlying distribution. Therefore, tests for comparisons

TABLE 13

LOCATIONS OF SIGNIFICANT DIFFERENTIATIONS BETWEEN CONCRETES

Laboratory No.	Test Method	Concretes Compared	Cycle Where Means Are Separated from Confidence Limits, Point A	Cycle Where Confidence Limits Separate, Point B	Cycle Where Difference Between Means Becomes Significant: $2\alpha = 0.1$, Point C	Cycle Where Difference Between Means Becomes Significant: $2\alpha = 0.05$, Point D
7	Rapid Air	HG-LG	4	28	4	11
1	Slow Air	HG-LG	108	150	102	115
3	Slow Air	HG-LG	58	78	59	68
9	Slow Air	HG-LG	167	285	168	230
1	Slow Water	HG-LG	23	30	23	26
8	Slow Water	HG-LG	7	42	5-8	5-8
10	Slow Water	HG-LG	13	17	13	15
13	Rapid Air	HG-LG	-	-	-[1]	-[1]
4	Rapid Air	HG-LG	-	-	-[2]	-
10	Slow Air	LG-HP	-	-	-[1]	-[1]

[1]Significant continuously from beginning.
[2]Not significant anywhere.

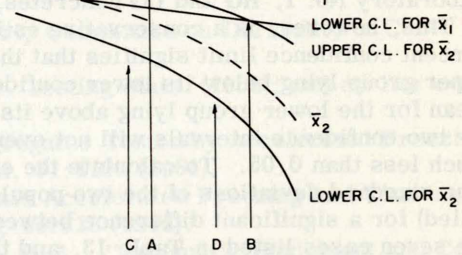
between means, such as the one used here, are insensitive to departure from normal distribution in the data.) The test used is one which determines whether a difference between the means of two groups of data is significantly large at a given probability level, assuming that the two groups come from populations with the same mean but with possibly different standard deviations.

Table 13 gives the results of the comparisons between means for the significant cases. A tabulation of all the comparisons at different numbers of cycles for different cases (Table 14) and an explanation of the statistical method used are given in Appendix B. The diagram associated with Table 13 (Fig. 33) is a hypothetical pair of confidence-interval curves with the curves of their associated means and illustrates the location on a typical curve of the points evaluated in Table 13. Points A and B are self-explanatory. Points C and D were found by testing the difference between means at a number of points until the first one at which the difference became significant (for the two probability levels) was located.

It will be noted that Point C, where the probability of a difference as large as, or larger than the observed difference, first reached 10 percent, was in every case with these data practically the same as Point A, the point where the mean with the narrower confidence interval crossed outside the limits for the wider confidence interval. In checking data from another program with a different number of specimens per sample, it was found that the test in this case became significant at the 10 percent level somewhat before Point A on the curves, but in no case was it later.

Point D in every case is found to be between A and B. (This also held true with the data from the other program previously mentioned.) Thus, in every case in this program the test could have been terminated at Point B and the means assumed to be significantly different, because the probability of a difference between sample means at least as large as the observed difference, if the means of the respective populations were not different, was less than 5 percent.

The relation between Point A and the 10 percent separation is not mathematically exact. However, in this program and the one previously mentioned, Point A could have been used as a point at which



A - Point where mean for group with narrower confidence limits crosses confidence limit for other group.

B - Point where lower confidence limit for upper group crosses upper confidence limit for lower group.

C - Typical position for point where difference between means becomes significant at 10% level (5% for one-sided test)

D - Typical position for point where difference between means becomes significant at 5% level (2.5% for one-sided test)

Figure 33. Hypothetical confidence-interval curves.

to begin testing the results to determine where the 5 percent level of significance was reached.

The difference for the case of Laboratory No. 13, rapid air (Fig. 6), where the upper confidence limit for LG concrete was practically coincident with the lower limit for HG concrete throughout the length of the former, was tested and found to be significant throughout. Also, the case where there was a wide observed separation between means, but one confidence interval was inside the other (Laboratory No. 4, rapid air) was tested and found not to have a significant difference.

PROBABILITY LEVELS

In all the comparisons made here a two-sided test was assumed. This means that no assumption was made as to which of the two means compared should have been the greater. If one mean had been expected beforehand to be higher than the other, a one-sided test would have been assumed, and the levels of probability for the same comparisons would have been 5 percent and 2.5 percent, respectively, instead of 10 percent and 5 percent.

The decision on whether a one- or two-sided test is applicable depends on the conditions of the experiment. In general, if two concretes are being compared, about whose relative durabilities nothing is known, either concrete could have the greater mean. In this case, the decision is made beforehand that if the absolute value of the difference between the measured means is not large enough to be significant, there is no difference between the two population means. Because a real difference would be assumed if the observed difference were either equal to or greater than a certain significant positive value or equal to or less than a corresponding negative value, this is a two-sided test, and the probabilities of 10 percent and 5 percent apply.

When more is known about the two concretes and one is expected beforehand to have a higher durability, the one-sided test applies. This would be the case where concrete mixtures of unknown durability were to be compared to a standard concrete mixture with a known record of high durability in a given test method (as, for example, the HG concrete from this program in either of the air-freeze methods). In this case the decision is made beforehand that the mean of the unknown concrete is to be subtracted from the mean of the reference concrete and a significant difference is to be recognized only if the observed difference is equal to or greater than the significant value in the positive direction.

In the present program the three concretes were designed to represent a range of durabilities, and, although there was no assumption beforehand about the relative durabilities of LG and HP concretes, the HG concrete was definitely expected to be the most durable of the three. Thus, in the comparisons between HG and LG concretes in Table 14, concrete HG was assumed to have the higher mean in each case, and the probabilities for points C and D could be assumed to be 0.05 and 0.025, respectively. Also, the statement could be made that if the tests had been terminated at Point B there would be a significant difference, because the probability of finding the observed difference between sample means, if no difference existed between the population means, would have been less than 2.5 percent. Also, if a 5 percent level of significance was desired and a one-sided test assumed, the test could have been terminated at Point A in all cases in this program.

When the actual point where the difference between means becomes significant is calculated as was done in this case, the test could be terminated before Point B even for a two-sided test. In determining when to terminate a test, however, it must be remembered that this statistical test only examines the significance of the difference between means at a certain point, and does not mean that a significant differentiation between concretes has occurred unless the two means continue to diverge. Thus, in many cases the test would need to be continued beyond the point where a significant difference was indicated in order to determine if the difference persisted. It appears that 5 to 10 cycles beyond Point B would have been sufficient for all the cases examined here.

Appendix B

Statistical Determination of Significant Difference Between Means

The statistic used in testing for a significant difference between means of samples from two populations with different variances is

$$V = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\dfrac{s_1^2}{\nu_1} + \dfrac{s_2^2}{\nu_2}}}$$

in which

$\bar{x}_1$ = mean relative dynamic modulus of concrete 1 (HG in the HG-LG comparisons);

$\bar{x}_2$ = mean relative dynamic modulus for concrete 2;

s_1, s_2 = corresponding estimates of standard deviation;

ν_1, ν_2 = corresponding degrees of freedom for the two samples.

This statistic is compared to the critical value, V, which is a function of the degrees of freedom for the two samples, the significance level, and the ratio of the observed sample variances. Values of V are found in the tables in references (19) or (20), the table used depending on the level of probability desired. When v is equal to or greater than V from the table, the statement can be made that the means are different. If the two means are diverging, the point at which v becomes equal to V in the chosen table can be taken as a statistical measure of the number of freezing-and-thawing cycles at which differentiation occurs. A tabulation of all the comparisons between means at different numbers of cycles for different cases is given in Table 14.

TABLE 14

COMPARISONS BETWEEN MEANS OF CONCRETES IN LABORATORY-METHOD

Lab. No.	Test Method	Concretes Compared	No. of Cycles	v	V: $2\alpha = 0.1$	V: $2\alpha = 0.05$
7	Rapid Air	HG-LG	28	2.66	1.80	2.21
			11	2.37	1.79	2.21
			10	2.16	1.79	2.20
			8	2.13	1.80	2.21
			7	1.88	1.79	2.20
			5	1.97	1.81	2.24
			4	1.82	1.82	2.24
13	Rapid Air	HG-LG	100	3.36	1.74	2.10
			10	2.79	1.75	2.13
4	Rapid Air	HG-LG	200	1.57	1.87	2.29
1	Slow Air	HG-LG	150	3.05	1.76	2.13
			130	2.63	1.76	2.14
			120	2.30	1.76	2.14
			115	2.18	1.77	2.15
			110	1.84	1.77	2.15
			108	1.85	1.77	2.15
			103	1.84	1.77	2.15
			102	1.81	1.76	2.14
			101	1.64	1.76	2.14
			50	0.61	1.81	
3	Slow Air	HG-LG	78	3.03	1.78	2.17
			70	2.36	1.78	2.18
			68	2.19	1.78	2.18
			65	2.02	1.78	2.18
			60	1.91	1.78	2.16
			58	1.70	1.76	2.14
			45	1.27	1.74	2.10
9	Slow Air	HG-LG	285	2.79	1.75	2.29
			230	2.27	1.82	2.25
			200	1.95	1.78	2.18
			170	1.93	1.73	2.09
			168	1.76	1.73	2.09
			167	1.67	1.73	2.09
			165	1.63	1.73	2.09
			160	1.59	1.73	2.09
10	Slow Air	LG-HP	15	2.76	1.82	2.26
			10	2.48	1.83	2.26
1	Slow Water	HG-LG	30	3.04	1.76	2.15
			26	2.38	1.79	2.18
			25	2.05	1.80	2.19
			23	1.82	1.81	2.22
8	Slow Water	HG-LG	42	2.51	1.85	2.29
			33	2.35	1.73	2.27
			8	2.29	1.74	2.11
			5	0	1.73	2.10
10	Slow Water	HG-LG	17	2.44	1.84	2.27
			15	2.38	1.82	2.24
			14	2.04	1.81	2.24
			13	1.93	1.82	2.25
			10	1.56	1.80	2.22

Appendix C

Laboratory No. 1 Side Program

When it became apparent that there would be a wide spread in results in the rapid-air tests, it was suggested that one laboratory make specimens and ship them to several of the other laboratories to be tested in their rapid-air apparatus, in order to determine whether this would eliminate some of the variation. Accordingly, beams of concretes similar to the LG and HP concretes were fabricated by Laboratory No. 1 and tested in Laboratories No. 1, 4, 7, 12, and 13.

The coarse aggregates for this series were the same as those used in the main program, but the fine aggregate was the laboratory "standard" sand usually used in Laboratory 1. The gravel was used in a mixture having an air content of 2.8 percent and the crushed limestone in concrete with a 6 percent air content. Because the water requirement of the sand was higher than that of the HRB sand, it was necessary to increase the water content to achieve a workable mixture and the cement content to give the same water-cement ratio as previously used. Mixture data are given in Table 15.

One batch of each concrete was mixed and 16 3- by 3- by 16¼-in. bars of each were cast. The bars were cured under water for seven days, then packed in wet sawdust in sealed crates and shipped. The specimens were to be stored under water when received and started in the rapid-air apparatus 28 days after casting. (Laboratories No. 12 and 13 were unable to start freezing-and-thawing tests on the day prescribed. The specimens were soaked until the end of the 28-day period, then sealed in plastic film and stored frozen until freezing-and-thawing tests could be started. Specimens for Laboratory No. 12 were thus stored 85 days and for No. 13, 13 days.)

Results of this side program are given in Tables 16 and 17. Table 16 gives weight changes at failure and durability factors for each laboratory. Table 17 gives the air-void parameters determined by traverses on sections of the hardened concrete. In Table 17, series LG and HP represent separate specimens of the two concretes which were not frozen. The others are specimens which were actually frozen and thawed in Laboratories No. 1 and 13, the ones from No. 13 being those which showed the lowest durability and the ones from No. 1 among those which showed the highest.

Wide variations in durability factors were evident in the side program as in the main program, lending further support to the belief that the freezing-and-thawing treatment given the specimens in different laboratories was not the same. Also, weight change varied from a weight gain, in a majority of instances, to a weight loss. With but one exception, concretes which lost weight were the more durable. Perhaps the concretes

TABLE 15

SIDE PROGRAM CONCRETE DATA

Mixture No.	Mixture Proportions by Oven Dry Weight	Cement (s/cy)	Slump (in.)	Air (percent)	Unit Weight (pcf)	W/C Ratio, by Weight	Air-Ent. Additive (ml/sk)
1	1: 2.5: 3.2	5.8	2.3	2.8	146.8	0.52	10.3
2	1: 2.3: 3.0	5.8	2.1	6.0	141.2	0.61	57.2

TABLE 16

WEIGHT CHANGE AND DURABILITY FACTORS, BY LABORATORY

Concrete	Beam	Change in Weight (gm)					Durability Factor				
		Lab. 1	Lab. 4	Lab. 7	Lab. 12	Lab. 13	Lab. 1	Lab. 4	Lab. 7	Lab. 12	Lab. 13
LG	A-1	-14	- 4	7	0	1	79.0 [1]	76.0	6.6	60.6	4.2
	A-2	- 5	-31	6	4	4	50.2	75.5	3.6	56.8	3.0 [1]
	A-3	-14	- 6	6	0	4	58.8	70.0	6.4	35.8	3.0
	Avg.	-11	-13.7	6.3	1	3	63.0	73.8	5.5	51.1	3.4
HP	C-1	+23	+27	18	23	21	19.2 [1]	18.6	6.0	7.6	8.2
	C-2	+23	+25	18	18	13	6.8	19.2	10.6	7.2	4.8
	C-3	+17	+24	19	18	12	15.8	12.2	9.8	8.2	4.6 [1]
	Avg.	+21	+25.3	18.3	20	15.3	13.9	16.7	8.8	7.7	5.9

[1] Air void parameters determined on these specimens after test (see Table 17).

TABLE 17

VOID PARAMETERS OF CONCRETE REPRESENTING THE APPARENTLY MOST DURABLE (LAB. NO. 1) AND LEAST DURABLE (LAB. NO. 13) IN THE RAPID-AIR METHOD, SIDE PROGRAM

Concrete	Specimen No.	Air Content (percent)	Average Chord Intercept (in.)	Specific Surface ($in.^{-1}$)	Voids Intercepted (no./in.)	Paste Content (percent)	Paste-Air Ratio	Spacing Factor, $\bar{L}$ (in.)	Durability Factor	Weight Change (gm)
LG	Series A[1]	3.57	0.0076	526	4.7	25.4	7.11	0.0103	-	-
	1A1	2.95	0.0101	396	2.9	25.4	8.61	0.0149	79	-14
	13A2	3.84	0.0129	308	3.0	25.4	6.62	0.0170	3	+4
HP	Series C[1]	6.46	0.0034	1,180	18.8	24.8	3.84	0.0033	-	-
	1C1	5.21	0.0045	889	11.6	24.8	4.76	0.0051	19.2	-23
	13C3	5.56	0.0041	976	13.5	24.8	4.46	0.0045	4.6	+13

[1] Parameters previously reported.

which gained weight failed because they became critically saturated.

From the results given in Table 17, it is apparent that wide variations existed in the void parameters of companion specimens from the same batch. This might account for the variable behavior of the specimens tested in a single laboratory, but the much wider variations of results between laboratories can hardly be completely explained on this basis, and are believed to be due to variations in freezing-and-thawing test equipment, rates of evaporation, absorption, etc.

Appendix D

Materials

COARSE AGGREGATE

Gravel

A brief petrographic description of the gravel used is given in the section on "Materials" in the body of the report.

Limestone

The following is from a petrographic report of the Concrete Division, U. S. Army Engineer Waterways Experiment Station, dated 17 February 1958:

1. Samples. On 23 December 1957, four bags weighing approximately 6 lb each of graded coarse aggregate in the ¾-, ½-, ⅜-in., and No. 4 sizes were received for petrographic analysis. This sample represents the material used as the "poor" coarse aggregate in the Highway Research Board cooperative freezing-and-thawing tests of concrete. Reference is also made to "Petrographic Data on Seven Rock Samples in Pore Structure Research," WES Misc. Paper No. 6-254, January 1958, pp. 5-7, in which one of the rocks studied, the Iowa dolomite (PCA-1), was obtained from the same source as this material and is very similar to the weathered dolomite, one of the lithologic varieties found in the present sample.

TABLE 18

X-RAY DIFFRACTION RESULTS OF "POOR" COARSE AGGREGATE SAMPLE

Constituent	Gray Dolomite	Cross-Bedded Dolomite	Weathered Dolomite	Partially-Weathered Dolomite	Dense Limestone	Fossiliferous Dolomitic Limestone	Chert and Dolomitic Chert
Nonclay minerals	Dolomite-Major Calcite-Major Quartz-Minor Feldspar-Trace	Dolomite-Major Calcite-Major Quartz-Minor Pyrite-Trace Feldspar-Trace	Dolomite-Major Calcite-Moderate Quartz-Minor Feldspar-Trace Pyrite (?) Trace	Dolomite-Major Calcite-Moderate Quartz-Minor Feldspar-Trace	Calcite-Major Dolomite-Trace Quartz-Trace	Dolomite-Major Calcite-Major Quartz-Minor Feldspar-Trace	Quartz-Major Dolomite-Minor Calcite-Trace Pyrite (?) Trace
Clay minerals	Illite-Trace 14-Å Clay[1]	Illite-Trace -	Illite-Trace Kaolin (?) Sl. Trace	Illite-Trace 14-Å Clay[1]	Absent -	Illite-Trace -	Absent -

[1] Present in amounts too small to be identified.

2. Summary. Petrographic and X-ray diffraction analyses of this aggregate sample show it to be made up of several varieties of dolomite and dolomitic limestone in various stages of weathering; limestone; and a small amount of chalcedonic chert. X-ray diffraction analyses indicate that this sample contains a very small amount of clay, mainly illite. No montmorillonite or other swelling clays were found. The results of X-ray diffraction analyses of the sample are given in Table 18.

TABLE 19

COMPOSITION OF "POOR" COARSE AGGREGATE SAMPLE

Constituents	Percentage in Fraction Retained[1]				Percentage in Whole Sample[2]
	¾-in.	½-in.	⅜-in.	No. 4	
Gray dolomite	28	31	35	31	31
Cross-bedded dolomite	16	16	10	12	14
Weathered dolomite	17	17	16	23	18
Partially-weathered dolomite	9	5	3	2	5
Dense limestone	12	19	21	17	18
Fossiliferous dolomitic limestone	13	8	11	11	10
Chert and dolomitic chert	5	4	4	4	4
Total	100	100	100	100	100

[1] Based on count of more than 300 particles in each sieve fraction.
[2] Based on gradation of sample, and on distribution of constituents by sieve fractions.

The percentage composition of each type (Table 19) is based on the grading of a previous sample of this same material. The following lithologic types of carbonate rocks were found:

(a) Gray dolomite. These particles, constituting about 31 percent of the sample, were composed of light gray, very fine-grained calcareous dolomite. They had a uniform granular texture and contained numerous small pores between the dolomite grains. Bulk specific gravity and absorption tests of these particles, results of which are given in Table 20, indicated that their porosity was rather high.

(b) Cross-bedded dolomite. These particles, constituting 14 percent of the sample, were similar to the gray dolomite but contained dark cross-bedded laminations and, although very fine-grained, had a considerably less uniform texture. Although no specific gravity and absorption tests were made on them, they were considered to be less porous than the gray dolomite.

(c) Weathered dolomite. These particles constituted 18 percent of the whole sample. They were composed of yellowish gray, thoroughly-weathered, fine-grained calcareous dolomite. Bulk specific gravity and absorption test results (Table 20) and thin sections indicated that these particles had a very high porosity.

(d) Partially-weathered dolomite. These very fine-grained calcareous dolomite particles were partly light gray and partly yellowish-gray in color. The yellowish-gray color was mainly due to the staining produced by the weathering of small pyrite grains found disseminated in the rock. There was no bedding plane at the contact between the weathered (yellowish-gray) and unweathered (light gray) zones. There was not sufficient material of this type to run bulk specific gravity and absorption tests, but examination of thin sections indicated that these particles have a porosity comparable to the light gray dolomite particles. They made up 5 percent of the sample.

(e) Dense limestone. These particles were composed of yellowish-gray, partially recrystallized, lithographic limestone, which was relatively unweathered. Bulk specific gravity and absorption test results (Table 20) and examination of thin sections indicated that they are only slightly porous. They make up 18 percent of the sample.

TABLE 20

SPECIFIC GRAVITY AND ABSORPTION OF ROCK TYPES IN "POOR" COARSE AGGREGATE

Lithologic Type	Bulk Specific Gravity[1]	Absorption (percent)
Gray dolomite	2.63	3.4
Weathered dolomite	2.52	5.9
Fossiliferous dolomitic limestone	2.61	3.7
Dense limestone	2.66	1.2

[1] Saturated surface dry.

(f) Fossiliferous dolomitic limestone. These particles, making up 10 percent of the sample, were composed of small, but irregular-sized dolomite rhombs, fossil shells and fragments, recrystallized calcite grains, and pyrite grains scattered throughout a very fine-grained carbonate matrix. Bulk specific gravity and absorption test results (Table 20), as well as thin sections, indicated the particles also had a high porosity.

(g) Chert and dolomitic chert. A small portion of the sample, 4 percent, was composed of light gray and yellowish-gray chert and dolomitic chert. The chert was present both as nodules and in cross-bedded layers. Both varieties are chalcedonic.

Inasmuch as thorough petrographic and X-ray diffraction analyses of this material indicated that there are no chemically deleterious minerals present other than a small amount of chalcedonic chert, it is believed that its physical properties (that is, the unusually high porosity and absorption, and low specific gravity) were responsible for the poor performance record of concrete using this material as coarse aggregate.

3. Test Procedure

(a) General. The particles were first washed to remove heavy surface coatings of rock dust. Samples of the dust were saved for later examination by X-ray diffraction. Representative samples of each sieve size were obtained by quartering and these particles were sorted into lithologic varieties by the examination of wet and dry particle surfaces, visually and with a stereoscopic microscope, using scratch tests and treatment with dilute hydrochloric acid. Selected particles of each lithology were sawed and the sawed surfaces etched with dilute hydrochloric acid and examined. Thin sections and immersion mounts of each lithologic type were made and their refractive indices and other optical properties were checked with a petrographic microscope. The bulk specific gravity, saturated surface-dry, and the absorption of the particles of each of four lithologic types were determined.

(b) X-ray diffraction. X-ray diffraction analysis was made of the wash-water residue containing the rock dust and of selected particles of each lithologic type to establish the presence and identification of any clay minerals present. Oriented clay slides were made of the wash-water residue; selected particles of each lithologic type were ground to pass a No. 325 sieve and oriented clay slides were made of each type. Tightly packed powder samples of each lithologic type were also examined to confirm the mineral composition obtained from regular petrographic analysis. In addition, small portions of the minus 325 samples representing three lithologic types were treated with 17.4 molar acetic acid and oriented clay slides were made of the residue. X-ray analyses of the samples were made on an XRD-3 X-ray diffractometer.

4. Description of Constituents. The composition and lithologic varieties of this sample are given in Table 19 and described below. X-ray diffraction analyses results are shown in Table 18.

(a) Gray dolomite. This lithologic type was the most numerous in each sieve fraction. The particles are light gray, very finely granular dolomite, some of which contain thin streaks of darker argillaceous material and pyrite. Thin sections of the rock show it to consist of very small, highly perfect dolomite rhombs and a smaller amount of anhedral carbonate grains. There was no zoning of the euhedral-anhedral grains. Although the carbonate grains were fairly tightly packed, there were numerous very small irregularly shaped pores between some grains. Very small opaque grains of pyrite were disseminated rather sparsely throughout the rock. The rock had the characteristic granular texture of dolomite and reacted only slightly with dilute hydrochloric acid. The bulk specific gravity of the particles was 2.63 and the absorption is 3.4 percent. The particles were mostly blocky, somewhat elongated in shape, and tended to become more tabular with decrease in size.

(b) Cross-bedded dolomite. These light gray particles appeared to be similar to the gray dolomite except that they contained more dark cross-bedded laminations, but examination of thin sections of this material revealed it to be composed of very fine-grained carbonate alternating with coarser highly perfect dolomite rhombs embedded in a matrix of extremely fine-grained carbonate along the laminations. The areas between the laminations were composed of tightly packed euhedral and anhedral carbonate grains that were quite small but varied considerably in size. A few small pyrite grains were disseminated in the rock and concentrated along the laminations. Small quartz grains were also present in the laminations. Although the predominant carbonate mineral present in this rock was dolomite, there was a considerable amount of calcite present as seen in grain mounts and the fairly vigorous reaction with dilute hydrochloric acid. The thin laminations of darker material in this rock did not appear to be distinct bedding planes. They were not planes of weakness. Most particles seemed to break across, rather than along, the laminations. The particles were blocky, elongated, and tabular in shape.

(c) Weathered dolomite. These particles were the typical yellowish-gray color of weathered dolomite. The rock was composed of highly perfect, very small dolomite rhombs and a small amount of larger, more irregularly shaped, carbonate grains. The grains were rather loosely packed and there was considerably more pore space between grains than in the other lithologic types in this sample. The bulk specific gravity of these particles was 2.52 and the absorption was 5.9 percent. The grain boundaries of the carbonate were generally iron-stained. Very small pyrite grains and limonite pseudomorphs after pyrite and possibly dolomite, although disseminated throughout the rock, were more highly concentrated along what were apparently bedding planes. The particles had a very fine-grained granular texture. The particles were soft and easily scratched with a needle and a finger nail. The particle shape was blocky and somewhat elongated, with very few tabular particles. Edges and corners were generally well-rounded and surfaces were smooth. Upon immersion in water most particles took up water and gave up small air bubbles. Their reaction to dilute hydrochloric acid was slight, and most of the acid was immediately soaked up by the particle.

(d) Partially-weathered dolomite. These particles were partly yellowish-gray, weathered, very fine-grained dolomite and partly light gray, very fine-grained dolomite, with no apparent bedding plane at the point of contact between the weathered and unweathered material. There was no difference in the grain size, hardness, and texture on opposite sides of the weathered-unweathered contact. Thin sections showed the rock to be composed of small, euhedral dolomite rhombs, irregular in size, loosely packed in a fine-grained carbonate matrix in some areas, and tightly packed in other areas. Most grains had very slightly iron-stained rims and the finer-grained matrix contains considerable staining. Small pyrite and limonite grains were scattered throughout the rock, particularly along bedding planes. These particles were not nearly so porous as the weathered dolomite. A few particles were fossiliferous, with the fossil shells being composed of milky calcite. The particles were blocky, pyramidal, and slightly tabular in shape, with subrounded edges and corners. The reaction of these particles with dilute hydrochloric acid was fairly vigorous.

(e) Dense limestone. These particles were composed of yellowish-gray dense lithographic limestone. Thin sections of the rock showed it to be composed of extremely fine-grained calcite that was partially recrystallized. The rock was probably once a fossiliferous pelleted limestone, although most of the fossils and pelleted structure have been destroyed by recrystallization. Recrystallized areas were very irregular in shape and size. They ranged from short thin areas resembling fracture fillings to large irregularly shaped areas that resemble cavity fillings. The grain size of the recrystallized calcite ranged from very small to fairly coarse. Some of the recrystallized areas appeared to be porous. The rock was composed entirely of calcite and reacted vigorously with dilute hydrochloric acid. The particle shape was irregular, with pyramidal and blocky particles predominating. The edges and corners of the particles were sharp and angular; surfaces are rough and conchoidal. These particles were unweathered. The bulk specific gravity of these particles was 2.66, the absorption 1.2 percent.

(f) Fossiliferous dolomitic limestone. These particles were composed of light gray extremely fine-grained dolomitic limestone with many small dark gray to black fossil shells, larger recrystallized calcite crystals, pyrite grains, and iron-stained flecks scattered throughout the matrix and along bedding planes. Thin sections of this material showed dolomite rhombs of varying sizes loosely scattered in the finely crystalline fossiliferous calcite matrix. The particles were fairly porous. The bulk specific gravity of these particles was 2.61, the absorption 3.7 percent. The particles were equidimensional, blocky, and tabular in shape and had subrounded edges and corners. The particles were fairly soft and seemed rather chalky in that they were very easily scratched with a needle and a chalky dust is easily rubbed off with the fingers. These particles reacted vigorously with dilute hydrochloric acid.

TABLE 21

SIEVE ANALYSIS OF SAND SAMPLES

Container No.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Fineness Modulus
	Cumulative Percent[1]							
(a) National Sand and Gravel Association[2]								
63	100.0	83.6	68.2	43.7	20.6	5.7	0.5	2.78
79	100.0	82.3	66.6	42.6	20.5	6.3	0.9	2.82
93	100.0	82.1	68.8	44.8	21.0	5.7	1.2	2.78
113	100.0	83.1	66.8	43.7	21.0	6.4	1.7	2.79
139	100.0	84.5	67.6	43.6	20.1	6.0	1.4	2.78
149	100.0	83.8	67.0	43.6	20.2	6.2	1.4	2.79
158	100.0	82.5	67.6	43.4	20.5	5.6	1.4	2.80
165	100.0	82.1	66.5	42.1	20.0	4.9	1.7	2.84
172	100.0	83.2	68.8	44.1	21.3	5.5	1.5	2.77
186	100.0	83.1	67.2	42.7	20.2	5.7	1.3	2.81
220	100.0	83.4	67.7	43.1	20.0	5.8	0.9	2.80
244	100.0	83.4	68.1	43.3	19.8	5.1	1.1	2.80
284	100.0	81.9	67.0	43.5	21.4	5.6	1.6	2.81
134	100.0	83.1	67.6	43.3	20.6	5.2	1.6	2.80
206	100.0	81.4	67.2	43.4	21.2	5.9	1.8	2.81
273	99.9	82.2	68.1	43.3	21.1	5.4	1.5	2.80
Avg.	100.0	82.9	67.6	43.4	20.6	5.7	1.3	2.80

(b) Ontario Hydro[3]

Sample No.	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100	No. 200	Fineness Modulus
1	0.7	16.8	32.3	56.8	81.0	95.3	-	2.79
2	0.0	16.6	31.8	56.2	79.7	95.1	-	2.79
3	0.0	16.2	32.1	55.8	80.1	94.9	-	2.79
4	0.0	17.8	32.9	56.6	80.0	95.0	-	2.82
5	0.0	17.0	32.8	56.5	80.3	95.3	-	2.82
6	0.0	17.1	33.7	56.5	80.5	95.3	-	2.83
7	0.3	17.1	32.1	56.3	80.4	95.1	-	2.80
8	0.0	16.8	32.7	56.1	79.8	95.2	-	2.81
9	0.4	17.2	32.2	56.6	80.2	95.1	-	2.79
10	0.3	17.4	32.2	56.0	79.8	95.3	-	2.79
11	0.8	17.4	33.1	57.4	80.4	95.0	-	2.79
12	0.4	17.0	32.5	56.6	80.2	95.0	-	2.79
13	0.0	16.6	32.3	56.6	80.1	95.3	-	2.81
14	0.2	17.0	33.3	57.1	80.3	95.5	-	2.82
Avg.	0.2	17.0	32.6	56.5	80.2	95.2	-	2.80

[1] Passing for N. S. G. A.; retained for Ontario Hydro.
[2] Tested by ASTM C 136, 27 April 1955.
[3] Tested by ASTM C 136, 4 Jan. 1955; one sample taken from each sealed container.

TABLE 22

COMPOSITION AND CONDITION OF SAND SAMPLE

Constituent	Number of Particles (percent)										
	In Fraction Retained on								In Whole Sample[4]		
	No. 4[1]	No. 8[2]	No. 16[2]	No. 30[2]	No. 50[2]	No. 100[2]	No. 200[2]	Passing No. 200[3]	Dense	Weathered	Total
Quartz	30	50	82	96	97	95	93	10	87	-	87
Chert, undiff.[5]	60	31	12	2	1	2	4	5	7	-	7
Chalcedony					tr	2	2		tr	-	tr
Feldspar	10	16	4	1	1	tr	1	5	3	-	3
Miscellaneous											
Sandstone		tr	-	-	-	-	-	-			
Granite	-	tr	1	-	-	-	-	-			
Concretions	-	tr	-	-	-	-	-	-	1	-	1
Mica	-	-	-	tr	tr	tr	tr	2			
Heavy minerals	-	-	-	-	-	-	tr	18			
Opaque	-	-	-	-	1	1	tr	tr			
Carbonates	-	-	-	-	-	-	tr	60	1	-	1
Unidentified	-	3	1	1	-	-	-	-	-	1	1
Total	100	100	100	100	100	100	100	100	-	-	-
Avg., weighted	-	-	-	-	-	-	-	-	99	1	100

[1] Based on examination of 60 particles in the petrographic sample.
[2] Based on counts of more than 300 particles in the sieve fraction.
[3] Based on examination of immersion mounts containing several thousand particles; estimated, not counted.
[4] Based on gradation of sample as received, and on distribution of constituents by sieve fractions.
[5] No determinations made of indices of refraction of chert retained on No. 30 sieve.

(g) Chert and dolomitic chert. These particles were made up of light gray and yellowish-gray fossiliferous and nonfossiliferous chert. The larger particles were mostly modular with encrustations of a soft very light gray chalky material, some of which reacted slightly with dilute hydrochloric acid. In other particles the chert was layered and cross-bedded. Thin sections of these particles showed numerous small rhombic to irregular shaped carbonate grains scattered more or less uniformly throughout a microcrystalline chert matrix. The chert was chalcedonic and there were numerous areas where the fibrous structure of the chert can be seen when viewed under high magnification. There were also many very small cubic and irregular-shaped pyrite grains scattered throughout the chert matrix, although they were more concentrated in some areas than in others. The shape of the particles was blocky and pyramidal; edges were mostly sharp and angular. Some of the nodular particles, however, had well-rounded edges and surfaces.

5. X-Ray Diffraction Analysis Results. The attempts to obtain minus 2-micron oriented clay slides from the minus 325 material using normal techniques failed, indicating that there was little minus 2-micron material in these samples. The use of a dispersing agent was necessary in order to keep enough clay-size material in suspension long enough to obtain a satisfactory oriented clay slide. Very little clay material was found in this aggregate sample. With the exception of the gray dolomite and partially-weathered dolomite containing traces of a 14-Å clay mineral that is not montmorillonite, illite and mixed-layer illite were the only clay minerals present.

Diffraction patterns of the seven lithologic varieties of this sample confirmed the mineral composition obtained by regular petrographic methods.

TABLE 23

RESULTS OF PHYSICAL TESTS OF SAND[1]

Test	Bulk Specific Gravity: Dry	Bulk Specific Gravity: Saturated Surface Dry	Apparent Specific Gravity	Absorption (percent)
1	2.60	2.62	2.65	0.67
2	2.60	2.62	2.65	0.65
Avg.	2.60	2.62	2.65	0.66

Sieve Size	Grading	Loss: Test 1	Test 2	Test 3	Average
(a) Sodium Sulfate, 5 Cycles					
4-8	17.1	5.8	7.2	7.6	6.9
8-16	15.3	2.1	2.3	2.5	2.3
16-30	24.2	1.3	1.0	1.1	1.1
30-50	22.8	0.3	0.3	0.3	0.3
Avg.[2]	-	1.7	1.9	2.0	1.9
(b) Magnesium Sulfate, 5 Cycles					
4-8		17.2	18.6	18.8	18.2
8-16		5.2	6.3	5.9	5.8
16-30		2.1	2.4	1.9	2.1
30-50		0.6	0.6	0.6	0.6
Avg.[2]		4.4	4.8	4.7	4.6
(c) Sodium Sulfate, 10 Cycles					
4-8		12.8	11.8	13.8	12.8
8-16		3.2	2.8	3.1	3.0
16-30		1.5	1.3	1.2	1.3
30-50		0.3	0.3	0.2	0.3
Avg.[2]		3.1	2.8	3.2	3.0
(d) Magnesium Sulfate, 10 Cycles					
4-8		22.2	21.8	20.9	21.6
8-16		7.3	7.3	7.9	7.5
16-30		2.6	2.4	2.3	2.4
30-50		1.0	0.8	0.8	0.9

[1] Performed at National Sand and Gravel Association laboratory.
[2] Weighted average.

FINE AGGREGATE

The following material is from a petrographic report of the Concrete Division, U. S. Army Engineer Waterways Experiment Station, dated 19 March 1958:

1. Sample. Approximately 10 tons of natural sand obtained from Green Brothers, in a single shipment, were processed through a laboratory six-deck vibrating screen during March and April 1954.

2. Grading

(a) Based on the sieve analyses of the individual size fractions produced by the separation, the calculated grading of the sand, if all fractions were recombined in the same proportions as they were produced, would have been as follows:

Sieve No.	Cumulative Percent Retained
4	1.4
8	7.0
16	17.3
30	51.4
50	90.7
100	99.1

(b) The material produced by the separation as the fraction coarser than No. 4 and material in certain other sizes present in excess of the amounts needed to approach the desired grading was processed through a roll crusher to provide additional material finer than No. 100.

(c) A total of 400 batches of sand were prepared and distributed to the cooperating laboratories. The batches contained either approximately 50 or 56 lb, depending on the size of concrete batch to be used at the various laboratories.

(d) Two laboratories performed sieve analyses on the individual batches of sand as received. These results are given in Table 21.

3. Composition and Condition. The composition and condition of a sample from this same source are given in Table 22.

4. Results of Physical Tests. Results of tests made by the National Sand and Gravel Association are given in Table 23.

Appendix E

Tables of Complete Data

Tables showing pertinent data about each laboratory, data about the fresh concrete mixtures, and final results on all specimens are given in this appendix. Tables 24, 25, 26, and 27 are self-explanatory.

In Tables 28 through 39 the unit weights at 2 and 14 days were calculated from the weights of the specimens in air and under water at the two ages given. Durability factors were calculated according to the formula given in the freezing-and-thawing methods, based on 60 percent of original dynamic modulus or 300 cycles. Thus, a D. F. equal to or less than 60 is one-fifth the number of cycles at which failure (60 percent of original dynamic E) occurred and a D. F. above 60 is numerically the same as the relative dynamic modulus at 300 cycles.

Weight at end of test and durability factor were obtained by interpolating to 60 percent of original E or to 300 cycles in cases where readings of dynamic modulus were not obtained at exactly these points.

TABLE 24

LABORATORY DATA

Laboratory No.	Size of Batch (cu yd)	Type of Mixer	Specimen Dimensions[1] (in.)	Aggregate, 7-Day Absorption (percent by weight)			Aggregate, Correction Factor for Air Meter (percent air)	
				Gravel	Limestone	Sand	Gravel	Limestone
1	0.033	Rotary drum	3x3x16¼	0.26	3.6	0.66	0.5	1.0
2	0.033	Rotary drum	4x3x16	0.35	3.6	0.66	0	0
3	0.033	Rotary drum	3x4x16	0.57	4.1	0.63	-	-
4	0.033	Lancaster	4x3x16	0.37	3.8	0.86	0.3	0.3
5	0.033	Rotary drum	3x4x16	0.30	3.6	0.10	Negl.[2]	Negl.[2]
6	0.041	Rotary drum	3½x4½x16	0.25	3.6	0.66	ND[3]	ND[3]
7	0.037	Rotary drum	3x3x11¼	0.40	3.8	0.80	-[4]	-[4]
8	0.036	Lancaster	3x4x16	0.35	3.5	-	ND[3]	ND[3]
9	0.033	Lancaster	3x4x16	0.42	4.0	ND[3]	1.0	1.0
10	0.037	Lancaster	3x3x11¼	0.44	3.9	0.61	0.2	0.2
11	0.033	Lancaster	4x3x16	0.50	4.1	0.63	0.1	0.2
12	0.037	Lancaster	4x3½x16	0.35	3.6	0.90	0	0
13	0.033	Rotary drum	3x4x16	0.4	3.9	0.50	0.20	0.25

[1] Width, depth, length; width is direction in which specimens were driven during sonic measurements.
[2] Negligible.
[3] Not determined.
[4] Stone and fine aggregate 0.2 percent.

TABLE 25

CHARACTERISTICS OF FRESHLY-MIXED LG CONCRETE

Batch No.[1]	Slump (in.)	Air-Entraining Agent (ml/sk)	Air Content (percent by vol)	Unit Weight (pcf)	Remarks
1A1	2.7	7.0	2.9	146.8	Batches for C 290 tests
1A2	3.2	7.0	2.7	148.1	
1A3	3.0	7.0	2.8	148.3	
1A1	3.0	7.0	2.6	147.7	Batches for C 291 tests
1A2	3.7	7.0	2.7	148.0	
1A3	3.0	7.0	2.3	148.0	
1A1	3.8	7.0	2.5	148.2	Batches for C 292 tests
1A2	3.6	7.0	2.5	148.8	
1A3	3.7	7.0	3.0	148.3	
1A1	3.7	7.0	2.4	148.8	Batches for C 310 tests
1A2	3.9	7.0	2.5	147.8	
1A3	3.6	7.0	2.5	148.4	
2A1	3.2	6.5	2.9	148.3	
2A2	2.8	5.4	2.7	148.9	
2A3	3.4	5.4	2.7	149.1	
3A2	3.5	6.5	2.4	148.7	
3A3	3.8	7.0	2.5	148.3	
3A4	3.8	10.0	2.9	147.9	
4A3	2.5	5.4	3.0	147.6	
4A4	2.6	4.9	2.9	148.0	
4A5	2.2	4.9	2.5	148.7	
5A1	2.8	6.5	2.5	147.5	
5A2	4.8	9.8	2.8	148.1	
5A3	3	9.8	2.6	148.5	0.25 lb H_2O withheld
6A1	2.8	11.2	2.8	148.2	
6A2	2.8	13.0	3.0	147.8	
6A3	2.8	12.5	3.0	147.6	
7A1	2	7.1	2.6	149.0	
7A2	2.1	7.8	2.7	149.2	
7A3	2.4	7.8	2.6	148.5	
8A1	2.5	6.5	3.1	147.6	
8A2	2.5	6.2	2.9	147.1	
8A3	2.7	6.2	2.8	147.8	
9A1	3.5	9.8	2.3	147.6	
9A2	3.0	11.5	3.0	146.8	
9A4	3.9	10.4	2.6	147.1	
10A1, 4	3.9	6.5	2.8	148.2	Six specimens cast from each batch and tested in two methods
10A2, 5	4.6	6.5	2.6	148.3	
10A3, 6	3.4	6.5	2.8	148.0	
11A1	2.5	7.2	2.2	149.4	
11A2	2.0	7.2	2.6	149.4	
11A3	2.7	7.2	2.3	149.8	
12A1	2.8	6.5	3.3	147.7	Batches for first C 291 tests
12A2	2.8	6.5	2.9	148.3	
12A3	2.8	6.5	3.0	148.3	
12A1	3.2	6.3	3.1	147.7	Batches for C 290 tests
12A2	3.0	6.1	2.6	148.3	
12A3	3.0	6.2	2.8	148.9	
12A1(R)	3.3	5.9	2.9	148.4	Batches for repeat C 291 tests
12A2(R)	3.4	5.8	2.8	149.0	
12A3(R)	2.6	5.8	2.8	149.0	
13A1	3.4	10.4	2.8	147.8	
13A2	3.6	8.9	2.4	147.8	
13A3	3.2	10.4	2.7	147.6	
13A4	4.1	10.4	2.8	148.0	
13A5	3.6	10.4	2.6	147.8	
13A6	5	10.4	2.9	147.2	
13A7	7.5	10.4	2.5	147.6	
13A8	6.8	10.4	2.7	147.2	
13A9	4.5	10.4	2.7	147.4	
13A10	3.5	10.4	2.8	147.6	
13A11	3.5	10.4	2.6	148.0	
13A12	3	10.4	2.7	147.4	

[1] Initial number indicates laboratory; R = repeat.

TABLE 26

CHARACTERISTICS OF FRESHLY-MIXED HG CONCRETE

Batch No.[1]	Slump (in.)	Air-Entraining Agent (ml/sk)	Air Content (percent by vol)	Unit Weight (pcf)	Remarks
1B1	3.0	57.0	6.8	143.4	Batches for C 290 tests
1B2	2.2	57.0	5.1	144.9	
1B3	3.4	61.8	6.8	143.1	
1B1	3.2	57.0	6.8	142.4	Batches for C 291 tests
1B2	2.9	57.0	6.2	144.0	
1B3	2.5	57.0	7.0	143.2	
1B1	3.7	54.5	6.3	143.6	Batches for C 292 tests
1B2	2.3	57.0	6.6	143.9	
1B3	2.9	57.0	6.8	143.1	
1B1	3.1	57.0	6.3	143.7	Batches for C 310 tests
1B2	3.9	57.0	7.7	140.8	
1B3	2.8	57.0	6.1	144.6	
2B1	2.7	54.0	6.6	143.5	
2B2	2.9	54.0	7.0	142.9	
2B3	2.8	48.6	6.8	143.3	
3B1	2.5	54.0	6.4	143.4	
3B3	3	52.0	7.1	141.5	
3B4	2.8	48.0	6.0	144.1	
4B3	3	33.8	7.0	142.2	
4B4	2.1	33.3	6.3	143.7	
4B5	2.4	33.3	6.1	144.0	
5B1	3	47.8	6.3	142.8	
5B2	5	47.8	7.0	140.0	0.25 lb H_2O added
5B3	3.5	47.8	6.5	142.3	
6B1	2.8	53.0	5.5	144.6	
6B2	2.5	58.3	5.8	144.0	
6B3	2.8	59.7	6.9	139.3	
7B1	2	49.0	5.7	144.4	
7B2	1.8	55.2	5.7	145.2	
7B3	2	64.0	6.3	143.9	
8B1	2.6	30.8	5.8	144.4	
8B2	2.6	31.8	6.4	143.1	
8B3	2.8	31.8	6.0	144.4	
9B1	2.9	40.5	6.0	142.2	
9B2	2.8	43.2	6.2	141.4	
9B3	2.8	43.2	6.5	141.0	
10B1, 4	3.2	37.5	6.8	142.8	Six specimens cast from each batch and tested in two methods
10B2, 5	2.7	36.5	6.7	143.5	
10B3, 6	3.7	36.5	7.0	142.0	
11B1	2.8	54.0	6.4	143.9	
11B2	2.0	54.0	6.5	144.3	
11B3	2.5	54.0	6.8	143.0	
12B1	2.0	46.5	7.0	143.4	Batches for C 291 tests
12B2	2.0	44.1	6.0	144.9	
12B3	2.0	46.5	6.2	144.0	
12B1	1.8	61.2	6.6	143.1	Batches for C 290 tests
12B2	2.0	61.2	6.0	144.3	
12B3	1.8	62.2	6.6	143.7	
13B1	2.5	41.3	6.6	141.8	
13B2	3.2	41.3	6.8	142.0	
13B3	3	41.3	7.0	141.4	
13B4	3.5	41.3	6.9	142.0	
13B5	2.9	41.3	6.4	142.2	
13B6	3	41.3	6.7	142.0	
13B7	3	41.3	7.0	141.8	
13B8	3	41.3	6.8	142.2	
13B9	2.4	41.3	6.3	142.4	
13B10	2.8	41.3	6.6	142.2	
13B11	2.9	41.3	6.5	141.6	
13B12	3	41.3	6.4	142.8	

[1]Initial number indicates laboratory.

TABLE 27

CHARACTERISTICS OF FRESHLY-MIXED HP CONCRETE

Batch No.[1]	Slump (in.)	Air-Entraining Agent (ml/sk)	Air Content (percent by vol)	Unit Weight (pcf)	Remarks
1C1	2.1	52.4	5.0	144.3	Batches for C 290 tests
1C2	2.0	60.5	4.4	144.5	
1C3	2.6	70.5	7.0	139.4	
1C1	3.2	50.9	7.1	140.6	Batches for C 291 tests
1C2	2.4	51.4	5.5	143.6	
1C3	2.2	51.4	4.2	145.1	
1C1	3.9	51.8	6.9	140.3	Batches for C 292 tests
1C2	2.5	51.4	5.7	142.7	
1C3	3.0	51.4	6.6	141.0	
1C1	3.5	53.4	7.0	139.8	Batches for C 310 tests
1C2	2.6	51.4	6.0	142.8	
1C3	2.3	51.4	6.0	143.2	
2C1	3.1	41.0	7.0	140.2	
2C2	2.9	33.5	6.0	143.5	
2C3	2.4	38.3	5.8	143.9	
3C1	3.5	43.0	7.0	141.1	
3C2	3.5	41.0	6.7	140.5	
3C3	3.5	40.0	6.6	140.7	
4C3	2.2	32.7	6.1	141.9	
4C4	1.9	33.3	6.3	142.3	
4C5	2.0	33.8	6.4	142.2	
5C1	2.2	45.3	6.0	141.5	0.25 lb H_2O added
5C2	2.2	46.6	6.2	141.1	0.25 lb H_2O added
5C3	2.2	45.3	6.4	140.8	0.25 lb H_2O added
6C1	2.5	62.9	6.4	141.4	
6C2	2.8	62.0	6.7	140.5	
6C3	2.8	61.1	6.5	141.2	
7C2	2.8	68.9	7.4	140.3	
7C3	1.8	58.4	5.8	143.4	
7C4	1.8	62.8	6.3	141.9	
8C1	2.7	32.6	6.5	141.8	
8C2	2.9	32.6	7.3	140.0	
8C3	2.6	32.4	6.6	141.6	
9C1	2.4	41.1	6.0	140.8	
9C2	2.2	43.9	6.0	141.4	
9C3	2.0	44.9	6.3	141.0	
10C1, 4	1.6	41.9	6.7	142.4	Six specimens cast from each batch and tested in two methods
10C2, 5	1.7	41.9	6.7	142.3	
10C3, 6	1.6	41.9	7.2	141.2	
11C1	1.2	62.0	5.6	143.0	
11C2	1.0	65.6	6.4	142.6	
11C3	1.2	65.6	6.1	143.0	
12C1	1.5	58.8	6.7	142.4	Batches for C 291 tests
12C2	1.5	63.6	6.8	142.2	
12C3	1.5	61.2	6.8	141.9	
12C1	1.5	65.1	6.0	143.1	Batches for C 290 tests
12C2	1.5	72.0	6.2	143.4	
12C3	1.8	71.0	6.4	142.5	
13C1	1.8	44.5	5.7	141.6	
13C2	2.4	44.5	6.0	141.4	
13C3	2.8	47.1	6.8	139.6	
13C4	2.8	44.5	6.3	141.1	
13C5	1.8	45.0	5.7	141.4	
13C6	2.5	44.5	6.4	140.2	
13C7	2.2	44.5	6.2	140.2	
13C8	2.5	46.1	6.9	139.0	
13C9	2.4	44.5	6.4	142.2	
13C10	2.8	44.5	6.8	139.2	
13C11	2.4	44.5	6.0	141.1	
13C12	2.2	44.5	6.3	140.5	

[1]Initial number indicates laboratory.

TABLE 28

RAPID-WATER TESTS, LG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1A1-1	2.9	149.4	149.4	5,620	5,620	5.81	6.4	0.020
2		149.1	149.3	5,670	5,660	5.88	8.4	0.026
3		149.0	149.3	5,682	5,670	5.86	11.2	0.047
1A2-1	2.7	150.6	150.8	5,734	5,722	5.86	6.6	0.026
2		150.8	151.4	5,740	5,724	6.36	6.2	0.034
3		150.5	150.6	5,730	5,726	5.79	5.4	0.028
1A3-1	2.8	150.8	150.8	5,728	5,724	5.81	5.4	0.026
2		150.3	150.2	5,722	5,715	5.88	8.4	0.036
3		150.3	150.3	5,720	5,718	5.71	6.2	0.044
6A1-1	2.8	150.0	151.0	9,961	9,925	6.23	6.6	
2		150.5	150.4	10,025	10,003	6.52	6.6	
3		150.1	150.6	9,988	9,974	6.24	6.6	
6A2-1	3.0	150.2	150.5	9,970	9,897	6.23	8.4	
2		149.9	150.3	9,929	9,862	5.97	8.8	
3		150.0	150.0	9,970	9,922	6.36	8.4	
6A3-1	3.0	148.2	149.7	9,929	9,886	6.33	5.8	
2		148.7	150.0	9,929	9,893	6.09	7.4	
3		148.4	150.2	9,957	9,835	6.04	5.6	
12A1-1	3.1	149.1	149.5	8,752	8,732	5.65	5.0	0
2		149.5	149.8	8,780	8,759	5.72	5.6	0
3		149.0	149.4	8,782	8,768	5.67	5.4	0
12A2-1	2.6	149.9	150.6	8,847	8,854	5.94	2.8	0.1
2		149.1	150.0	8,816	8,804	5.92	4.0	0
3		149.3	150.4	8,858	8,850	5.83	3.6	0
12A3-1	2.8	149.3	150.4	8,836	8,813	5.94	6.4	0
2		149.4	150.2	8,815	8,777	5.80	5.0	0
3		149.6	150.5	8,820	8,804	5.81	4.8	0.1
13A1-1	2.8	149.3	149.8	7,570	7,532	5.44	10.6	
2-2	2.4	149.8	150.5	7,493	7,489	5.70	5.6	
3-3	2.7	149.7	150.1	7,555	7,533	5.81	6.4	
13A5-1	2.6	149.6	150.0	7,646	7,627	5.68	6.2	
6-2	2.9	149.4	149.7	7,477	7,437	5.40	8.8	
7-3	2.5	149.1	149.5	7,499	7,489	5.39	8.0	
13A9-1	2.7	149.7	149.8	7,603	7,554	5.55	8.4	
10-2	2.8	149.5	149.8	7,531	7,328	5.27	7.8	
11-3	2.6	149.6	149.9	7,580	7,496	5.80	11.0	

[1] Batches 1A1, 1A2, and 1A3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.

TABLE 29

RAPID-WATER TESTS, HG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1B1-1	6.8	145.4	145.9	5,582	5,413	5.18	48.2	0.029
2		145.2	145.6	5,584	5,408	5.17	47.6	0.025
3		143.6	144.8	5,496	5,327	5.21	45.0	0.024
1B2-1	5.1	146.5	147.5	5,610	5,515	5.55	33.2	0.036
2		146.4	147.3	5,582	5,465	5.60	31.2	0.029
3		146.7	147.1	5,618	5,514	5.64	31.6	0.038
1B3-1	6.8	145.3	145.7	5,540	5,384	5.20	44.0	0.034
2		145.7	146.1	5,580	5,403	5.18	52.8	0.031
3		145.2	145.8	5,550	5,402	5.04	50.0	0.029
6B1-1	5.5	146.4	147.4	9,693	9,389	5.59	38.8	
2		146.5	147.6	9,734	9,436	5.62	41.6	
3		146.7	147.7	9,789	9,476	5.65	39.4	
6B2-1	5.8	147.0	147.4	9,789	9,490	5.53	35.0	
2		146.3	146.8	9,825	9,560	5.79	34.2	
3		146.6	147.3	9,793	9,513	5.65	34.4	
6B3-1	6.9	142.7	144.6	9,621	9,196	5.22	52.0	
2		142.8	144.4	9,684	9,187	5.25	56.8	
3		142.6	144.3	9,594	9,217	5.31	49.0	
12B1-1	6.6	145.2	146.2	8,611	7,874	5.45	71.8	
2		145.2	146.2	8,569	8,024	5.47	67.8	
3		144.8	145.8	8,572	7,852	5.36	77.1	
12B2-1	6.0	145.6	146.7	8,669	8,178	5.65	53.0	
2		145.5	146.5	8,626	[3]	[3]	[3]	
3		145.1	146.3	8,622	8,020	5.62	50.0	
12B3-1	6.6	145.0	145.9	8,626	8,128	5.51	59.2	
2		144.9	145.8	8,539	8,074	5.45	52.6	
3		145.3	146.4	8,582	8,097	5.42	52.8	
13B1-1	6.6	144.3	144.9	7,387	6,889	5.11	58.2	
2-2	6.8	142.5	143.4	7,191	6,698	4.65	62.0	
3-3	7.0	143.6	144.3	7,255	6,820	4.85	80.3	
13B5-1	6.3	143.7	144.5	7,278	6,917	4.97	51.8	
6-2	6.7	143.3	144.2	7,296	6,883	5.05	80.3	
7-3	7.0	143.4	144.3	7,307	6,869	5.06	69.9	
13B9-1	6.3	144.7	145.2	7,387	6,971	5.08	69.4	
10-2	6.6	143.8	144.4	7,367	6,934	5.14	58.8	
11-3	6.5	143.6	144.3	7,315	6,823	5.07	68.1	

[1] Batches 1B1, 1B2, and 1B3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Damaged in handling.

TABLE 30

RAPID-WATER TESTS, HP CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1C1-1	5.0	145.8	146.2	5,540	5,555	4.41	3.0	0.051
2		145.2	145.7	5,562	5,585	4.21	3.6	0.068
3		146.9	146.7	5,562	5,576	4.51	3.0	0.061
1C2-1	4.4	146.2	146.9	5,620	5,632	4.57	4.2	0.061
2		146.5	147.1	5,622	5,640	4.51	3.6	0.065
3		145.7	146.7	5,594	5,612	4.38	3.2	0.084
1C3-1	7.0	142.1	142.6	5,410	5,435	4.00	6.0	0.063
2		141.5	142.1	5,410	5,431	3.92	6.4	0.055
3		141.9	142.5	5,410	5,433	3.88	5.8	0.070
6C1-1	6.4	143.9	144.5	9,594	9,607	4.36	4.0	
2		144.0	144.6	9,562	9,528	4.35	6.4	
3		143.9	144.3	9,557	9,565	4.25	4.8	
6C2-1	6.7	143.4	144.7	9,566	9,535	4.15	8.0	
2		143.4	144.0	9,562	9,453	4.25	7.6	
3		143.0	143.6	9,585	9,510	4.24	6.8	
6C3-1	6.5	142.6	144.0	9,634	9,627	4.38	8.2	
2		142.0	143.8	9,630	9,619	4.28	8.4	
3		142.2	144.0	9,644	9,636	4.39	8.2	
12C1-1	6.0	144.3	145.8	8,637	8,655	4.66	6.0	
2		143.9	145.6	8,561	8,578	4.57	4.2	0.1
3		144.4	146.0	8,654	8,659	4.47	5.4	0.1
12C2-1	6.2	144.9	145.9	8,573	8,587	4.48	4.6	0
2		144.8	145.9	8,614	8,636	4.60	5.2	0.1
3		144.8	146.0	8,622	8,636	4.55	4.8	0.1
12C3-1	6.4	143.9	145.4	8,548	8,555	4.31	5.6	0.1
2		143.6	145.2	8,561	8,568	4.52	6.2	0.1
3		143.8	145.4	8,564	8,573	4.37	6.4	0.1
13C1-1[3]	5.7	143.3	144.0	7,266	7,289	4.14	6.8	
2-2	6.0	143.9	144.5	7,334	7,349	3.87	5.8	
3-3	6.8	141.3	142.3	7,265	7,287	4.00	5.6	
13C5-1[3]	5.7	143.4	144.0	7,320	7,346	4.03	6.0	
6-2	6.4	142.4	143.1	7,263	7,282	4.00	6.0	
7-3	6.2	143.2	143.8	7,315	7,332	4.20	8.8	
13C9-1	6.4	142.2	143.0	7,233	7,255	3.95	6.0	
10-2	6.8	141.2	141.9	7,025	7,040	3.56	7.4	
11-3	6.0	143.4	143.9	7,325	7,326	4.00	5.4	

[1] Batches 1C1, 1C2, and 1C3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Excluded from averages.

TABLE 31

RAPID-AIR TESTS, LG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1A1-1	2.6	149.8	150.3	5,904	5,892	5.83	28.8	0.073
2		149.5	150.0	5,912	5,898	5.79	27.8	0.072
3		149.9	150.6	5,883	5,872	5.82	22.2	0.090
1A2-1	2.7	150.7	151.2	5,885	5,878	5.96	24.8	0.110
2		150.2	150.5	5,941	5,942	5.74	24.4	0.090
3		150.0	150.4	5,848	5,832	5.92	23.8	0.058
1A3-1	2.3	150.7	151.2	5,814	5,814	5.90	21.0	0.094
2		150.3	150.7	5,886	5,889	5.48	15.8	0.048
3		150.5	150.8	5,868	5,864	5.72	23.4	0.090
2A1-1	2.9	150.5	150.8	7,764	7,772	6.03	4.6	
2		150.2	150.6	7,617	7,625	6.02	4.4	
3		149.6	149.9	7,737	7,747	6.11	4.4	
2A2-1	2.7	150.7	151.0	7,610	7,620	5.95	2.8	
2		150.6	150.9	7,893	7,902	6.70	3.2	
3		150.6	151.0	7,925	7,933	6.44	5.6	
2A3-1	2.7	150.4	150.8	7,754	7,762	6.13	2.4	
2		150.7	151.1	7,874	7,881	6.26	2.4	
3		151.0	151.4	7,694	7,698	6.02	2.6	
4A3-1	3.0	149.5	149.7	7,606	7,580[3]	5.92	92.7	
2		149.1	149.0	7,751	7,710[3]	6.27	98.6	
3		148.9	149.0	7,469	7,428[3]	5.83	99.5	
4A4-1	2.9	149.1	150.0	7,631	7,585[4]	5.93	98.9	
2		149.7	150.3	7,630	7,592[4]	6.06	97.7	
3		149.6	150.4	7,716	7,681[4]	6.13	98.5	
4A5-1	2.5	150.4	151.0	7,510	7,487	5.97	36.4	
2		150.4	151.0	7,648	7,625	6.10	43.8	
3		149.9	150.5	7,677	7,654	6.10	46.8	
5A1-1	2.5	150.8	151.2	7,620	7,618	6.24	2.2	
2		150.5	151.0	7,596	7,594	6.11	2.4	
3		150.5	150.9	7,589	7,580	6.11	2.9	
5A2-1	2.8	150.5	151.0	7,587	7,580	6.16	8.8	
2		150.4	150.9	7,614	7,609	6.18	8.4	
3		150.1	150.9	7,636	7,628	6.25	9.2	
5A3-1	2.6	150.4	151.0	7,705	7,703	6.03	4.5	
2		150.2	150.7	7,631	7,631	6.03	3.9	
3		150.2	150.8	7,662	7,655	6.33	4.2	
7A1-1	2.6	149.9	151.0	4,041	4,038	5.99	52.4	
2		150.8	151.7	4,084	4,083	6.02	39.6	
3		150.6	151.6	4,053	4,056	6.30	19.0	
7A2-1	2.7	150.4	151.4	4,062	4,066	6.14	45.8	
2		150.5	151.6	4,045	4,051	6.10	37.6	
3		150.2	151.4	4,109	4,112	6.46	24.8	
7A3-1	2.6	150.4	151.2	4,093	4,096	6.25	37.4	
2		151.3	152.0	4,050	4,052	6.11	26.4	
3		150.7	151.5	4,128	4,131	6.55	20.8	
11A1-1	2.2	151.6	151.3	7,773	7,770	5.68	4.4	0.067
2		151.6	151.6	7,755	7,753	5.41	3.2	0.044
3		151.0	151.6	7,843	7,840	6.05	4.6	0.047
11A2-1	2.6	152.3	152.9	7,810	7,812	5.90	2.8	0.049
2		152.3	152.9	7,954	7,955	6.03	3.8	0.062
3		152.3	152.3	7,911	7,914	5.56	4.6	0.060
11A3-1	2.3	151.6	151.6	7,799	7,798	5.47	4.8	0.078
2		151.6	151.6	8,008	8,008	5.85	3.0	0.047
3		151.6	152.3	7,688	7,690	5.60	3.4	0.053
12A1-1	3.3	148.3	149.5	8,796	8,732	5.62	102.1	0
2		148.6	149.7	8,832	8,773	5.76	100.0	0
3		148.5	149.5	8,853	8,809	5.77	101.0	0
12A2-1	2.9	149.3	150.4	8,967	8,900	6.02	96.5	0.1
2		149.1	150.2	8,944	8,890	6.13	97.5	0.1
3		148.8	150.0	8,858	8,800	5.89	91.2	0.1
12A3-1	3.0	148.8	149.7	8,852	8,818	5.89	98.0	0.1
2		148.9	149.9	8,854	8,804	5.89	100.0	0
3		148.7	149.7	8,868	8,809	5.90	101.0	0
12A1-1R	2.9	148.6	149.4	8,829	8,732	5.88	96.5	0
2R		148.7	149.4	8,785	8,700	5.73	96.6	0
3R		149.1	149.7	8,806	8,759	5.86	95.5	0.1
12A2-1R	2.8	149.1	149.7	8,905	8,845	5.93	98.9	0
2R		148.9	149.5	8,850	8,786	5.89	84.5	0.1
3R		149.1	149.5	8,931	8,890	6.13	75.9	0.1
12A3-1R	2.8	149.3	150.0	8,998	8,877	6.11	90.9	0.1
2R		149.6	150.1	8,846	8,791	6.06	54.4	0.1
3R		149.8	150.3	8,948	8,881	6.19	59.2	0.1
13A1-2	2.8	149.4	149.8	7,583	7,524	5.64	76.5	
2-3[5]	2.4	150.0	150.4	7,400	7,391	5.50	22.8	
4-1	2.8	149.3	149.6	7,612	7,561	5.60	41.2	
13A5-2	2.6	149.5	149.8	7,584	7,548	5.50	29.4	
6-3	2.9	149.4	149.7	7,463	7,408	5.36	33.2	
8-1	2.7	148.7	149.1	7,524	7,494	5.18	69.4	
13A9-2	2.7	149.3	149.6	7,534	7,488	5.53	37.8	
10-3	2.8	149.1	149.5	7,428	7,355	5.33	83.5	
12-1	2.7	149.3	149.9	7,599	7,566	5.52	58.8	

[1] Batches 1A1, 1A2, and 1A3 are different batches from those with same numbers tested by the other three methods in this laboratory; R = repeat batch.
[2] Air content of freshly-mixed concrete.
[3] Final weight at 430 cycles.
[4] Final weight at 417 cycles.
[5] Excluded from average.

TABLE 32

RAPID-AIR TESTS, HG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1B1-1	6.8	145.7	146.5	5,777	5,750	5.41	97.0	0.019
2		144.6	145.6	5,777	5,746	5.18	93.6	0.016
3		145.2	146.2	5,741	5,716	5.21	97.6	0.016
1B2-1	6.2	146.5	147.2	5,690	5,670	5.42	99.3	0.010
2		146.4	147.1	5,753	5,736	5.31	94.6	0.012
3		146.7	147.5	5,678	5,654	5.48	93.5	0.010
1B3-1	7.0	145.7	146.6	5,620	5,610	5.32	81.4	0.030
2		144.9	145.7	5,576	5,570	5.23	78.3	0.027
3		144.5	145.4	5,550	5,542	5.22	94.3	0.016
2B1-1	6.6	144.9	145.6	7,485	7,447	5.54	97.2	
2		144.7	145.5	7,735	7,709	6.61	96.0	
3		145.1	145.8	7,630	7,594	5.92	96.8	
2B2-1	7.0	143.9	144.5	7,313	7,282	5.17	98.1	
2		144.4	145.0	7,278	7,239	5.24	98.1	
3		144.2	144.9	7,352	7,321	5.20	99.0	
2B3-1	6.8	145.0	145.8	7,830	7,797	6.02	98.2	
2		144.6	145.3	7,520	7,484	5.73	96.3	
3		145.0	145.8	7,406	7,372	5.43	97.2	
4B3-1	7.0	143.3	144.1	7,439	7,393	5.81	92.6	
2		143.5	144.4	7,418	7,379	5.38	101.1	
3		143.4	144.7	7,426	7,385	5.46	100.3	
4B4-1	6.3	145.0	145.8	7,379	7,335	5.45	102.0	
2		144.2	145.5	7,524	7,490	5.58	100.3	
3		145.5	146.4	7,299	7,260	5.39	99.8	
4B5-1	6.1	144.8	145.7	7,474	7,435	5.63	101.6	
2		144.7	145.4	7,308	7,255	5.83	92.7	
3		145.0	145.8	7,348	7,307	5.58	100.7	
5B1-1	6.3	145.7	146.4	7,459	7,415	5.57	100.4	
2		145.7	146.4	7,380	7,353	5.41	100.6	
3		145.7	146.3	7,460	7,434	5.57	101.5	
5B2-1	7.0	144.1	144.9	7,339	7,311	5.18	102.5	
2		143.9	144.8	7,356	7,321	5.34	101.5	
3		144.1	145.1	7,437	7,411	5.35	99.6	
5B3-1	6.5	145.6	146.1	7,376	7,309	5.31	102.9	
2		145.4	145.9	7,373	7,298	5.26	100.9	
3		145.4	146.0	7,354	7,312	5.29	101.3	
7B1-1	5.7	146.8	148.0	3,965	3,960	5.87	97.1	
2		146.6	147.7	3,910	3,911	5.79	96.5	
3		146.2	147.3	4,023	4,022	6.21	96.0	
7B2-1	5.7	146.4	147.4	3,970	3,965	5.81	97.6	
2		145.9	147.2	3,948	3,942	5.60	99.5	
3		146.3	147.7	3,981	3,980	6.04	98.8	
7B3-1	6.3	145.3	146.5	3,918	3,917	5.66	98.4	
2		144.8	146.0	3,894	3,892	5.42	97.6	
3		145.2	146.5	3,968	3,968	5.59	98.5	
11B1-1	6.4	145.4	146.0	7,532	7,479	4.69	98.7	0.007
2[3]		144.8	145.4	7,452	7,404	4.84	97.5	0.000
3[3]		145.4	146.0	7,365	7,316	4.63	97.6	0.000
11B2-1[3]	6.5	146.6	147.9	7,485	7,433	4.98	100.0	0.000
2		147.3	147.9	7,520	7,459	4.92	100.0	0.000
3		146.6	147.3	7,495	7,443	4.84	101.2	0.000
11B3-1	6.8	144.8	145.4	7,497	7,442	4.90	97.6	0.007
2		144.8	145.4	7,361	7,310	4.78	98.7	0.007
3		144.8	145.4	7,475	7,420	5.13	92.0	0.007
12B1-1	7.0	143.6	144.8	8,612	8,573	5.67	101.0	0
2		143.2	144.4	8,620	8,573	5.34	103.0	0
3		143.1	144.2	8,582	8,541	5.48	101.0	0
12B3-1	6.0	144.7	145.8	8,706	8,659	5.50	104.2	0
2		144.9	145.9	8,745	8,696	5.76	103.1	0
3		145.4	146.4	8,741	8,700	5.70	102.0	0
12B3-1	6.2	145.0	146.1	8,735	8,682	5.52	103.1	0
2		144.7	145.9	8,720	8,682	5.51	102.1	0
3		144.4	145.6	8,663	8,627	5.48	102.1	0
13B1-2	6.6	143.9	144.5	7,275	7,240	4.68	97.0	
2-3	6.8	143.2	144.0	7,388	7,359	5.08	95.3	
4-1	6.9	143.7	144.5	7,323	7,286	5.07	96.5	
13B5-2	6.4	143.8	144.6	7,313	7,282	4.95	99.0	
6-3	6.7	143.5	144.4	7,361	7,328	5.20	98.8	
8-1	6.8	143.1	143.8	7,257	7,218	4.94	97.2	
13B9-2	6.3	145.4	145.9	7,366	7,332	5.23	97.7	
10-3	6.6	143.8	144.3	7,378	7,334	5.10	96.2	
12-1	6.4	143.8	144.5	7,357	7,313	5.04	98.1	

[1] Batches 1B1, 1B2, and 1B3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Beams slightly abraded through handling.

TABLE 33

RAPID-AIR TESTS, HP CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1C1-1	7.1	143.7	144.7	5,655	5,661	3.92	8.6	0.126
2		143.9	144.7	5,655	5,660	3.96	9.4	0.117
3		143.4	144.3	5,640	5,645	4.08	7.8	0.116
1C2-1	5.5	146.3	147.2	5,666	5,681	4.38	5.8	0.114
2		146.0	146.8	5,722	5,742	4.31	7.8	0.126
3		145.9	146.7	5,653	5,672	4.51	6.2	0.108
1C3-1	4.2	146.7	147.4	5,649	5,667	4.57	7.0	0.108
2		146.4	147.2	5,677	5,700	4.44	8.6	0.094
3		147.4	147.7	5,586	5,615	4.51	6.6	0.110
2C1-1	7.0	143.0	143.7	7,283	7,299	4.11	10.0	
2		143.0	143.5	7,148	7,173	3.78	15.4	
3		143.1	143.6	7,446	7,465	4.25	8.0	
2C2-1	6.0	144.7	145.4	7,280	7,293	4.15	8.4	
2		144.6	145.1	7,399	7,419	4.22	7.8	
3		144.8	145.4	7,569	7,582	4.44	5.6	
2C3-1	5.8	144.9	145.6	7,300	7,317	4.09	7.4	
2		144.9	145.6	7,240	7,255	4.04	7.8	
3		145.1	145.7	7,496	7,514	4.42	7.4	
4C3-1	6.1	143.4	144.4	7,473	7,451	4.48	21.6	
2		143.3	143.7	7,333	7,354	4.29	21.0	
3		144.2	144.2	7,304	7,326	4.26	22.4	
4C4-1	6.3	143.5	144.6	7,414	7,425	4.34	19.8	
2		143.2	144.6	7,332	7,347	4.33	18.0	
3		143.3	144.6	7,402	7,420	4.44	18.0	
4C5-1	6.4	142.5	143.2	7,337	7,330	4.23	14.4	
2		142.2	143.2	7,264	7,278	4.10	22.6	
3		141.4	142.5	7,285	7,301	4.09	21.4	
5C1-1	6.0	144.9	145.4	7,362	7,380	4.24	7.7	
2		144.4	145.1	7,309	7,329	4.13	5.6	
3		144.0	144.7	7,309	7,321	4.26	8.4	
5C2-1	6.2	144.4	145.2	7,255	7,277	4.18	5.8	
2		144.9	145.4	7,274	7,293	4.20	10.7	
3		144.1	144.7	7,328	7,344	4.27	7.5	
5C3-1	6.4	144.0	144.6	7,400	7,406	4.27	7.2	
2		144.4	145.1	7,387	7,389	4.35	6.9	
3		144.1	144.4	7,375	7,375	4.26	8.8	
7C2-1	7.4	141.6	143.1	3,833	3,850	4.30	15.6	
2		142.4	144.1	3,863	3,879	4.30	11.6	
3		141.6	143.1	3,889	3,907	4.44	14.7	
7C3-1	5.8	145.1	146.5	3,931	3,937	4.38	12.2	
2		144.6	145.9	3,962	3,967	4.74	5.8	
3		144.6	145.8	3,982	3,993	4.77	9.2	
7C4-1	6.4	143.7	145.2	3,926	3,928	4.45	6.4	
2		144.1	145.5	3,936	3,946	4.71	10.8	
3		144.4	145.8	3,981	3,992	4.74	9.1	
11C1-1	5.6	145.4	146.6	7,493	7,506	4.05	4.6	0.087
2		146.0	146.6	7,452	7,467	4.10	3.2	0.050
3		146.6	147.3	7,512	7,525	4.28	3.8	0.049
11C2-1	6.4	144.1	145.4	7,542	7,557	3.91	7.2	0.073
2		143.5	144.8	7,450	7,461	3.85	5.8	0.087
3		144.8	145.4	7,584	7,601	3.91	6.4	0.078
11C3-1	6.1	144.8	145.4	7,611	7,625	3.91	6.0	0.068
2		144.8	145.4	7,256	7,267	3.81	9.0	0.073
3		145.4	146.0	7,433	7,450	3.93	6.2	0.067
12C1-1	6.7	142.5	144.0	8,573	8,578	4.38	18.0	0.1
2		142.6	144.1	8,569	8,578	4.37	18.6	0.1
3		142.3	143.9	8,529	8,546	4.20	17.4	0.1
12C2-1	6.8	142.6	143.9	8,514	8,532	4.20	22.4	0.2
2		142.8	144.3	8,555	8,564	4.17	13.4	0.1
3		142.9	144.3	8,582	8,605	4.38	14.2	0.1
12C3-1	6.8	143.0	144.4	8,595	8,618	4.38	15.4	0.1
2		143.4	144.8	8,617	8,636	4.40	16.4	0.1
3		142.5	144.0	8,526	8,550	4.35	17.8	0.2
13C1-2[3]	5.7	143.3	144.0	7,376	7,397	4.22	8.6	
2-3	6.0	143.6	144.2	7,309	7,324	3.94	5.6	
4-1	6.3	141.7	142.9	7,243	7,263	4.15	10.0	
13C5-2[3]	5.7	143.3	144.0	7,303	7,318	4.05	6.2	
6-3	6.4	142.5	143.3	7,288	7,305	4.03	6.2	
8-1	6.9	141.1	141.6	7,227	7,229	3.90	3.0	
13C9-2	6.4	141.7	142.4	7,078	7,095	3.84	8.8	
10-3	6.8	141.3	141.8	7,142	7,159	3.77	9.0	
12-1	6.3	142.9	143.5	7,324	7,337	3.98	5.4	

[1] Batches 1C1, 1C2, and 1C3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Excluded from average.

TABLE 34

SLOW-WATER TESTS, LG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1A1-1	2.5	150.6	151.0	5,893	5,815	5.62	14.4	0.125
2		150.4	151.2	5,942	5,809	5.79	17.2	[3]
3		150.7	151.3	5,842	[4]	5.80	[4]	[4]
1A2-1	2.5	150.6	151.2	5,844	5,777	5.98	11.8	0.089
2		150.5	151.0	5,918	5,853	5.92	11.6	0.078
3		150.6	151.0	5,867	5,781	5.78	16.6	0.089
1A3-1	3.0	149.8	150.2	5,721	5,686	5.75	21.6	0.078
2		150.3	150.5	5,729	5,608	5.77	18.4	0.113
3		150.1	150.5	5,745	5,595	5.62	26.2	0.090
8A1-1	3.1	150.3	151.1	7,578	7,306	5.92	13.8	
2		150.0	150.9	7,578	7,275	5.90	11.8	
3		150.3	150.8	7,610	7,478	6.17	9.8	
8A2-1	2.9	149.9	150.2	7,586	7,166	5.56	13.4	
2		150.3	150.8	7,641	7,429	6.00	12.2	
3		150.1	150.4	7,583	7,132	5.87	13.0	
8A3-1	2.8	150.1	150.6	7,645	7,381	6.16	6.6	
2		149.6	150.2	7,588	7,324	5.87	13.0	
3		150.3	150.7	7,608	7,227	5.96	11.4	
10A1-1	2.8	150.4	150.9	4,009	3,810	5.82	17.4	0.097
2		150.6	151.1	4,029	3,840	5.83	19.2	0.100
3		150.8	151.3	4,031	3,868	5.70	17.4	0.100
10A2-1	2.6	150.2	150.7	4,033	3,827	5.85	22.8	0.090
2		150.4	151.3	4,014	3,820	5.90	19.0	0.092
3		150.3	150.8	4,049	3,843	5.70	23.4	0.090
10A3-1	2.8	150.4	150.9	4,018	3,764	5.92	27.0	0.100
2		150.4	151.0	4,014	3,762	5.89	27.4	0.087
3		150.0	150.7	4,039	3,749	6.03	29.0	0.093
13A1-3	2.8	149.7	150.1	7,675	6,699	5.90	7.8	
3-1	2.7	149.1	149.4	7,371	6,881	5.35	10.2	
4-2	2.8	149.3	149.7	7,612	7,606	5.73	7.0	
13A5-3	2.6	149.8	150.1	7,598	7,603	5.61	5.4	
7-1	2.5	-	150.1	7,538	7,441	5.27	7.8	
8-2	2.7	149.1	149.4	7,543	7,528	5.44	6.6	
13A9-3	2.7	149.3	149.7	7,521	7,489	5.60	6.2	
11-1	2.6	149.6	149.9	7,598	7,291	5.78	9.0	
12-2	2.7	149.3	149.7	7,562	7,164	5.66	9.4	

[1] Batches 1A1, 1A2, and 1A3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Insert damaged.
[4] Broken in handling at 24 cycles.

TABLE 35

SLOW-WATER TESTS, HG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1B1-1	5.0	145.8	146.7	5,732	5,437	5.33	55.4	0.106
2		145.9	146.7	5,766	5,537	5.34	49.0	0.068
3		145.9	146.8	5,709	5,439	5.17	44.4	0.081
1B2-1	4.8	146.0	146.8	5,607	5,356	5.61	52.0	0.084
2		145.9	146.7	5,748	5,381	5.42	51.2	0.087
3		146.2	147.0	5,625	5,512	5.55	31.6	0.032
1B3-1	5.2	145.1	146.0	5,576	5,260	5.40	46.2	0.056
2		145.9	146.7	5,601	5,338	5.37	37.0	0.064
3		145.9	146.6	5,596	5,297	5.39	53.6	0.073
8B1-1	5.8	146.7	147.3	7,450	6,620	5.74	37.4	
2		147.5	148.0	7,514	5,892	5.71	25.8	
3		147.0	147.6	7,456	7,009	5.70	22.6	
8B2-1	6.4	145.5	146.3	7,434	6,297	5.49	43.4	
2		145.6	146.3	7,414	6,236	5.44	45.0	
3		145.6	146.3	7,396	6,614	5.45	32.2	
8B3-1	6.0	146.1	146.7	7,466	6,600	5.57	35.4	
2		146.0	146.6	7,444	6,322	5.58	46.2	
3		146.1	146.7	7,481	6,440	5.48	41.4	
10B1-1	6.8	146.2	146.7	3,922	3,570	5.22	40.0	0.050
2		145.9	146.6	3,864	3,282	5.16	74.2	0.046
3		145.9	146.5	3,879	3,418	5.16	56.4	0.042
10B2-1	6.7	145.5	146.1	3,923	3,386	5.50	81.8	0.039
2		145.6	146.4	3,942	3,354	5.50	84.4	0.045
3		145.9	146.4	3,907	3,369	5.36	66.2	0.046
10B3-1	7.0	145.5	146.3	3,897	3,305	5.36	58.2	0.055
2		145.1	145.8	3,881	3,413	5.30	49.6	0.057
3		145.0	145.8	3,874	3,571	5.39	34.8	0.038
13B1-3	6.6	143.6	144.2	7,344	6,236	5.02	29.2	
3-1	7.0	143.5	144.3	7,300	6,760	4.84	24.8	
4-2	6.9	143.8	144.6	7,308	6,737	4.76	19.6	
13B5-3	6.4	143.6	144.4	7,305	6,413	5.19	27.2	
7-1	7.0	142.9	143.8	7,360	6,773	5.13	22.8	
8-2	6.8	143.1	143.8	7,247	6,139	4.95	26.0	
13B9-3	6.3	145.0	145.6	7,399	7,108	5.19	17.4	
11-1	6.5	143.6	144.4	7,328	7,048	5.05	17.2	
12-2	6.4	143.5	144.4	7,318	7,117	5.13	14.6	

[1] Batches 1B1, 1B2, and 1B3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.

TABLE 36

SLOW-WATER TESTS, HP CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1C1-1	6.9	142.6	143.6	5,514	5,514	3.87	8.8	0.141
2		142.8	144.0	5,596	5,596	3.88	6.4	0.133
3		141.7	142.7	5,504	5,504	3.82	6.0	0.136
1C2-1	5.7	144.4	145.5	5,587	5,588	4.24	5.6	0.134
2		144.4	145.9	5,576	5,678	4.20	4.4	0.109
3		144.4	145.9	5,582	5,579	4.16	5.6	0.147
1C3-1	6.8	143.7	145.7	5,562	5,556	4.11	6.4	0.142
2		143.3	146.4	5,539	5,534	3.95	6.2	0.148
3		143.7	146.4	5,507	5,518	4.17	7.4	0.141
8C1-1	6.5	144.0	144.6	7,298	7,150	4.12	8.8	
2		143.5	144.3	7,305	7,104	4.21	8.8	
3		144.3	145.0	7,329	7,209	4.25	8.4	
8C2-1	7.3	142.1	142.9	7,175	7,048	3.89	9.8	
2		142.5	143.2	7,237	6,872	4.01	12.2	
3		142.6	143.3	7,259	7,054	3.91	10.8	
8C3-1	6.6	143.6	144.5	7,370	7,162	4.22	9.8	
2		144.2	145.0	7,324	7,163	4.21	8.8	
3		143.3	144.1	7,318	7,114	4.28	11.4	
10C1-1	6.7	146.1	146.6	3,959	3,838	4.34	10.6	0.125
2		145.9	146.4	3,956	3,910	4.37	8.0	0.065
3		146.6	147.3	3,957	3,877	4.46	10.0	0.080
10C2-1	6.7	145.2	145.8	3,920	3,748	4.47	18.0	0.230
2		145.0	145.5	3,918	3,746	4.21	14.4	0.148
3		145.0	145.6	3,906	3,589	4.11	12.6	0.259
10C3-1	7.2	144.9	145.6	3,934	3,865	4.36	10.2	0.100
2		144.6	145.4	3,901	3,828	4.33	10.4	0.155
3		144.7	145.5	3,900	3,855	4.53	8.8	0.111
13C1-3[3]	5.7	143.4	144.0	7,389	7,421	4.35	3.6	
3-1	6.8	141.0	142.2	7,199	7,243	4.12	3.6	
4-2	6.3	142.2	142.9	7,251	7,282	3.94	3.6	
13C5-3[3]	5.7	143.5	144.0	7,317	7,348	4.11	3.2	
7-1	6.2	143.0	143.6	7,310	6,832	4.14	5.2	
8-2	6.9	141.4	142.0	7,207	7,197	3.89	2.8	
13C9-3	6.4	141.5	142.1	7,022	6,752	3.71	4.0	
11-1	6.0	143.4	144.0	7,239	7,267	4.09	3.6	
12-2	6.3	143.2	144.0	7,304	7,336	4.13	3.8	

[1] Batches 1C1, 1C2, and 1C3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Excluded from average.

TABLE 37

SLOW-AIR TESTS, LG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1A1-1	2.4	150.3	150.8	5,945	5,920	5.77	98.9	0.062
2		151.1	151.6	6,035	6,020	5.77	101.7	0.039
3		151.0	151.7	5,989	5,966	5.75	102.9	0.040
1A2-1	2.5	150.5	150.9	5,878	5,864	5.80	101.7	0.046
2		150.2	150.8	5,903	5,882	5.74	102.8	0.039
3		150.7	151.0	5,868	5,848	5.90	100.6	0.050
1A3-1	2.5	150.4	150.8	5,740	5,730	5.54	101.8	0.047
2[3]		150.4	150.7	5,722	5,714	5.88	68.6	0.114
3		150.5	150.8	5,720	5,712	5.82	104.1	0.038
3A2-1	2.4	149.7	150.4	7,653	7,628	5.58	35.0	
2		149.9	150.8	7,592	7,597	5.76	45.0	
3		149.4	150.3	7,541	7,531	5.49	46.2	
3A3-1	2.5	149.3	150.0	7,575	7,547	5.61	41.4	
2		149.5	150.1	7,565	7,533	5.59	44.4	
3		149.6	150.4	7,536	7,518	5.42	36.0	
3A4-1[3]	2.9	150.2	150.1	7,545	7,523	5.72	82.2	
2		150.2	150.2	7,560	7,547	5.50	37.6	
3		149.9	150.2	7,573	7,562	5.55	44.2	
9A1-1	2.3	149.5	149.8	7,573	7,573	5.61	66.1	
2		148.9	149.4	7,537	7,547	5.63	90.4	
3		149.2	149.6	7,552	7,559	5.70	73.7	
9A2-1	3.0	148.7	149.4	7,640	7,645	5.76	101.3	
2		148.6	149.3	7,615	7,597	5.88	102.6	
3		148.6	149.4	7,622	7,641	5.75	90.0	
9A4-1	2.6	148.8	149.4	7,511	7,497	5.57	106.1	
2		149.1	149.8	7,517	7,518	5.62	104.4	
3		148.9	149.5	7,512	7,520	5.73	93.8	
10A4-1	2.8	151.0	151.6	4,057	4,058	5.82	21.0	0.066
2		150.9	151.4	4,052	4,050	5.84	13.2	0.074
3		150.9	151.4	4,022	4,024	5.72	16.8	0.126
10A5-1	2.6	149.9	150.5	4,020	4,020	5.73	20.8	0.071
2		150.5	151.0	4,071	4,060	5.82	26.6	0.139
3		150.3	150.8	4,021	4,019	5.86	16.8	0.120
10A6-1	2.8	150.7	150.9	3,983	3,984	5.98	23.2	0.066
2		150.0	150.7	4,005	4,004	5.74	24.4	0.053
3		150.4	150.9	3,996	3,988	5.98	25.6	0.052
13A2-1	2.4	150.2	150.6	7,486	7,448	5.40	110.1	
3-2	2.7	149.2	149.6	7,335	7,301	5.25	109.0	
4-3	2.8	149.4	149.8	7,513	7,476	5.56	106.4	
13A6-1	2.9	149.5	149.8	7,442	7,393	5.27	108.5	
7-2	2.5		149.9	7,530	7,487	5.46	109.3	
8-3	2.7	148.7	149.0	7,478	7,426.	5.43	108.3	
13A10-1	2.8	149.3	149.7	7,505	7,458	5.41	108.1	
11-2	2.6	149.1	149.4	7,589	7,542	5.50	110.7	
12-3	2.7	148.8	149.4	7,586	7,543	5.64	107.6	

[1] Batches 1A1, 1A2, and 1A3 are different batches from those with same numbers tested by the other three methods in this laboratory.
[2] Air content of freshly-mixed concrete.
[3] Excluded from average.

TABLE 38

SLOW-AIR TESTS, HG CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1B1-1	6.3	145.9	146.9	5,746	5,726	5.28	106.6	0.010
2		145.7	146.9	5,790	5,764	5.30	107.2	0.008
3		145.3	146.4	5,690	5,664	5.24	107.9	0.008
1B2-1	7.7	143.2	144.4	5,508	5,476	5.04	106.2	0.009
2		142.9	143.9	5,562	5,534	5.03	104.9	0.008
3		143.7	144.7	5,562	5,540	5.04	105.0	0.009
1B3-1	6.1	147.0	147.7	5,654	5,640	5.55	108.4	0.011
2		146.7	147.4	5,652	5,624	5.50	107.2	0.010
3		146.2	147.0	5,608	5,878	5.56	108.4	0.006
3B1-1	6.4	145.9	146.5	7,384	7,316	5.06	107.8	
2		144.8	146.4	7,346	7,287	5.22	109.3	
3		146.1	146.4	7,332	7,267	5.16	109.3	
3B3-1	7.1	143.7	144.9	7,317	7,270	4.99	107.8	
2		143.6	144.7	7,238	7,198	5.03	107.9	
3		143.4	144.8	7,289	7,225	4.94	108.1	
3B4-1	6.0	146.5	146.6	7,466	7,403	5.24	104.9	
2		146.3	146.5	7,422	7,354	5.24	106.3	
3		145.7	146.4	7,369	7,301	5.25	106.5	
9B1-1	6.0	145.0	146.2	7,429	7,407	5.22	106.8	
2		145.3	146.4	7,432	7,398	5.19	106.8	
3		144.9	146.0	7,405	7,365	5.46	104.2	
9B2-1	6.2	143.7	145.0	7,423	7,385	5.47	102.1	
2		144.0	145.2	7,466	7,423	5.47	102.6	
3		143.8	144.9	7,480	7,444	5.23	105.8	
9B3-1	6.5	143.6	145.0	7,346	7,306	5.10	105.7	
2		143.2	144.5	7,312	7,266	5.11	106.8	
3		143.2	144.6	7,332	7,289	5.00	107.4	
10B4-1	6.8	146.7	147.3	3,923	3,907	5.25	105.5	0.006
2		146.8	147.0	3,929	3,909	5.28	104.5	0.006
3		146.2	146.5	3,891	3,876	5.16	106.6	0.006
10B5-1	6.7	144.1	144.9	3,886	3,866	5.27	105.1	0.005
2		145.7	146.3	3,923	3,905	5.27	105.5	0.001
3		145.1	145.8	3,910	3,893	5.34	105.6	0.003
10B6-1	7.0	145.0	145.7	3,876	3,855	5.26	105.0	0.005
2		145.1	145.9	3,854	3,833	5.23	105.1	0.002
3		146.2	146.9	3,937	3,916	5.40	106.7	0.001
13B2-1	6.8	143.6	144.7	7,333	7,275	4.98	106.2	
3-2	7.0	143.4	144.2	7,253	7,202	5.02	108.0	
4-3	6.9	143.4	144.0	7,263	7,205	4.72	108.3	
13B6-1	6.7	143.3	144.2	7,307	7,258	5.06	107.8	
7-2	7.0	142.6	143.6	7,275	7,217	4.82	108.3	
8-3	6.8	142.8	143.8	7,253	7,197	4.84	109.0	
13B10-1	6.6	144.5	145.1	7,432	7,370	5.20	105.8	
11-2	6.5	143.5	144.3	7,440	7,388	5.18	106.1	
12-3	6.4	143.6	144.3	7,357	7,296	5.15	107.2	

[1] Batches 1B1, 1B2, and 1B3 are different batches from those with same numbers tested by the other three methods in this laboratory.

[2] Air content of freshly-mixed concrete.

TABLE 39

SLOW-AIR TESTS, HP CONCRETE SPECIMENS

Specimen No.[1]	Air Content[2] (percent by vol)	Unit Weight (pcf)		Weight (gm)		Dynamic Modulus at 14 Days (psi x 10^{-6})	Durability Factor	Expansion at End of Test (percent)
		2 Days	14 Days	At 14 Days	At End of Test			
1C1-1	7.0	141.7	143.1	5,483	5,489	3.94	14.0	0.100
2		141.4	142.7	5,617	5,624	3.72	15.2	0.094
3		141.3	142.4	5,486	5,489	3.90	13.4	0.101
1C2-1	6.0	144.7	145.5	5,546	5,550	4.41	11.6	0.072
2		144.7	145.9	5,652	5,657	4.29	11.0	0.121
3		144.9	145.9	5,602	5,602	4.24	7.0	0.078
1C3-1	6.0	144.8	145.7	5,563	5,582	4.31	8.6	0.111
2		145.7	146.4	5,604	5,619	4.40	7.8	0.090
3		145.7	146.4	5,595	5,612	4.49	10.0	0.093
3C1-1	7.0	143.8	144.4	7,240	7,253	3.77	18.2	
2		143.9	144.5	7,245	7,239	3.85	15.0	
3		143.3	144.7	7,277	7,290	3.80	14.0	
3C2-1	6.7	143.3	143.7	7,236	7,245	3.91	20.4	
2		143.4	143.6	7,247	7,238	3.74	13.4	
3		143.1	143.6	7,184	7,180	3.73	16.0	
3C3-1	6.6	143.4	143.8	7,294	[3]	3.84	[3]	
2		144.0	144.6	7,274	7,254	3.73	16.8	
3		143.0	144.2	7,263	7,274	3.90	16.8	
9C1-1	6.0	143.6	144.8	7,381	7,405	4.24	7.8	
2		143.7	144.8	7,380	7,360	4.21	10.0	
3		143.7	144.8	7,404	7,425	4.11	6.6	
9C2-1	6.0	143.7	144.6	7,320	7,340	4.15	8.4	
2		144.1	145.0	7,343	7,358	4.08	7.6	
3		144.3	145.2	7,341	7,361	4.16	7.4	
9C3-1	6.3	142.2	143.8	7,303	7,323	4.03	8.0	
2		142.5	144.2	7,325	7,340	4.04	7.2	
3[4]		142.8	144.6	7,340	7,355	4.02	4.2	
10C4-1	6.7	145.6	146.2	3,924	3,930	4.26	6.0	0.088
2		145.1	145.8	3,925	3,929	4.37	7.2	0.081
3		146.2	146.8	3,954	3,959	4.46	7.4	0.076
10C5-1	6.7	144.8	145.4	3,897	3,904	4.14	9.6	0.109
2		144.9	145.5	3,906	3,908	4.24	12.4	0.184
3		145.0	145.7	3,897	3,904	4.41	6.4	0.066
10C6-1	7.2	144.4	145.2	3,895	3,889	4.46	9.6	0.116
2		144.3	144.8	3,892	3,901	4.31	10.2	0.101
3		144.4	145.2	3,878	3,889	4.32	8.4	0.174
13C2-1	6.0	143.2	144.1	7,297	7,274	3.96	31.8	
3-2	6.8	140.9	142.1	7,180	7,189	3.92	27.2	
4-3	6.3	142.0	142.7	7,216	7,133	3.92	25.6	
13C6-1	6.4	142.0	142.6	7,259	7,240	4.02	12.2	
7-2	6.2	143.1	143.6	7,209	7,198	3.89	17.2	
8-3	6.9	141.6	142.1	7,085	[3]	3.74	[3]	
13C10-1	6.8	140.8	141.4	7,156	7,136	3.78	15.6	
11-2	6.0	142.7	143.2	7,273	7,219	3.84	34.8	
12-3	6.3	143.1	143.7	7,279	7,240	4.11	35.2	

[1] Batches 1C1, 1C2, and 1C3 are different batches from those with same numbers tested by the other three methods in this laboratory.

[2] Air content of freshly-mixed concrete.

[3] Broken during test.

[4] Excluded from average.

Appendix F
Suggested Operating Procedures

This research has produced no evidence that any of the ASTM freezing-and-thawing test methods in its present form is both sufficiently quantitative and reproducible to provide absolute limits for the routine acceptance or rejection, on a general basis, of concrete or concrete materials. The methods do, however, provide useful procedures for comparing the relative durability of different concretes within a given laboratory. In that connection, the Committee recommends attention to the following precautions:

1. Concretes to be compared should be mixed at as nearly the same time as feasible, placed into and removed from curing at the same time, and exposed to freezing and thawing concurrently.
2. Each class of concrete should be represented by at least three batches, preferably mixed on different days. It is desirable to have three or more test specimens from each batch as a check on within-batch uniformity. As indicated under item 1, all classes of concrete to be compared should be mixed on each mixing day.
3. Air content of the concrete should be known as accurately as possible, and, if the object is to evaluate relative durability of a given concrete, the air content of the freezing-and-thawing specimens should duplicate as closely as possible that of the given concrete. If aggregate is the variable under study, the air content should be sufficiently high to provide positive frost protection for the cement paste. For all concretes to be compared, the air content should be the same within ± 0.5 percentage point. Each specimen should be weighed in air and under water to provide an indication of uniformity. Whenever possible the air content and air-void characteristics should be determined by microscope examination of the hardened concrete specimens, and preferably on specimens which have actually been frozen and thawed.
4. Unless aggregate saturation is a controlled variable, the aggregates for all classes of concrete should be soaked in water for seven days after they have been dried to essentially constant weight in air. The aggregates must not be allowed to dry out before incorporation in concrete. Necessary adjustments must be made in the quantity of mixing water to compensate for the free moisture retained by the aggregates.
5. Unless mixing condition or treatment of the fresh concrete is a variable, extreme care should be exercised to assure that the procedures for mixing and handling the concrete and fabricating specimens are as nearly identical as possible for all classes of concrete which are to be compared.
6. Unless treatment of test specimens is a controlled variable, all specimens should be identically protected and cured between the time of molding and exposure to freezing and thawing. One acceptable sequence of operations is as follows:

   (a) Immediately after molding, place the specimens in a fog room (relative humidity not less than 95 percent) at 73 ± 3 F, covered with at least four layers of wet burlap.

   (b) After 24 ± 4 hr, strip the specimens and immerse them immediately in a saturated limewater solution at 73 ± 3 F. This operation shall be handled in such a way that the time between removal from the molds and immersion in the limewater is held to an absolute minimum and no surface drying of the specimens occurs.

   (c) Remove specimens from the limewater at the same age (14 days unless otherwise specified) and, after necessary measurements of weight and fundamental frequencies, place them in the thawing environment of the test exposure, taking care to minimize drying during handling.
7. Every effort should be made to assure that all specimens to be compared receive the same exposure to freezing and thawing. Ability to accomplish this may depend not only on the characteristics of the apparatus but also on the arrangement and location of the specimens. Turning specimens end for end and changing locations in the apparatus each time specimens are returned after measurement will help to minimize the effects of unavoidable differences in environment.
8. Supplementary tests and the keeping of detailed records will often be helpful in accounting for poor reproducibility of test results. Changes in weight of specimens during curing may reveal differences in saturation of presumably identical specimens. Measurements of density may provide a check on uniformity of air content. Obviously, records of such things as equipment breakdowns and deviations from prescribed methods may be vital in interpreting test data. Such records are readily made at the time, but are often impossible to reconstruct after the tests are completed.

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