EFFECT OF ENTRAINED AIR ON STRENGTH AND DURABILITY OF CONCRETE MADE WITH VARIOUS MAXIMUM SIZES OF AGGREGATE

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SYNOPSIS

DESPITE considerable past experience with the use of air entrainment in concrete, there are frequent and increasing demands for quantitative information concerning the proper amount of entrained air for adequate resistance to freezing and thawing and salt scaling and as to the effect of entrained air on the strength of various concretes.

The data in this report cover tests of concretes made with three cement contents, 4, 5.5, and 7 sacks per cu. yd. and five maximum sizes of aggregate, No. 4, ⅜-in., ¾-in., 1½-in., and 2½-in. The consistency of all concretes was 2 to 3 in. as measured by the slump test. One fine aggregate and one coarse aggregate were used. For each combination of cement content and maximum size of aggregate, eight concretes were prepared with air contents covering a fairly wide range.

The results of freezing-and-thawing tests indicate that for the concretes whose prior curing included a period of air-drying, adequate resistance to freezing and thawing is secured at a relatively constant amount of entrained air in the mortar fraction, regardless of cement content or maximum size of aggregate. For these tests, this amount of air in the mortar fraction was approximately 9 percent. Concretes cured continuously moist required somewhat more entrained air for the same resistance to freezing and thawing.

The report also includes information on the effect of entrained air on strength, resistance to salt scaling, volume change, and absorption of these concretes.

INTENTIONAL air entrainment in the manufacture of concrete is now a well-established practice. The benefits of entrained air in producing durable, frost-resistant concrete have been thoroughly demonstrated. However, quantitative information has been lacking as regards the proper amount of entrained air for adequate frost resistance and the effect of the entrained air on the strength of concretes, particularly those made with various maximum sizes of aggregate.

Much of the laboratory and field experience with air-entrained concrete was based upon pavement mixes made with 1½-in. maximum-size aggregate and has resulted in the specification of 3 to 6 percent of entrained air for concrete resistant to frost action. Studies of pavement concrete made with sand-gravels from the Kansas-Nebraska-Iowa-Missouri area indicate the desirable range of air contents to be about 5 to 8 percent. These sand-gravels contain little material coarser than ⅜ in., and the air contents obtained with a non-air-entraining cement range from 3 to 4 percent. These results indicate the desirability of establishing the air requirements of concretes made with various maximum sizes of aggregate and suggest the possibility that specifying the air content of the mortar fraction might be a more suitable procedure than specifying the air content on a total concrete-volume basis.

This study was undertaken with this objective in mind. In addition, the data provide information on the effect of entrained air on the flexural and compressive strengths of the concretes investigated.

SCOPE OF TESTS

The concretes used in this study had cement contents of 4.0, 5.5, and 7.0 sacks per cu. yd. and a consistency of 2 to 3 in., as measured by the slump test. For each cement content, five maximum sizes of aggregate were used: No. 4 mesh, ⅜-in., ¾-in., 1½-in. and 2½-in. Generally, eight concretes were prepared for a particular cement content and maximum size of aggregate, with the air contents of these concretes ranging from those obtained with Type I cements to air contents beyond those obtained with Type IA cements, the intermediate air-contents being obtained by the use of various blends of Type I and IA cements and the higher air-contents by addition of neutralized vinsol resin in solution to Type IA cement during mixing.

The concretes prepared were subjected to the following tests: (1) flexural and compres-

sive strength tests of 6- by 6- by 30-in. beams at age of 28 days; (2) for $5\frac{1}{2}$ sacks per cu. yd. concretes only—flexural and compressive strength tests of 6- by 6- by 30-in. beams and compressive strength tests of 6- by 12-in. cylinders at ages of 3, 7, and 28 days and one year; (3) freezing-and-thawing tests of 3- by 3- by $11\frac{1}{4}$-in. prisms; (4) resistance to surface scaling resulting from the use of salts for ice removal; and (5) characteristics of the air voids in the hardened concretes, *e.g.*, bubble spacing factors.

MATERIALS

The cements used were Type I blend and Type IA blend prepared from three cements from different sources and purchased in the Chicago area. The chemical compositions, calculated potential compound compositions, and results of various physical tests of the cements are shown in Tables 1, 2, aad 3. Tensile and compressive strengths of mortars are shown in Table 4.

The fine aggregate used was sand from Elgin, Illinois. This sand is a predominantly dolomitic natural sand. The coarse aggregate was a highly siliceous crushed gravel from Eau Claire, Wisconsin. Both aggregates have excellent field service records. Grading, specific gravity, and absorption data for these aggregates are shown in Table 5.

The aggregates were air-dried and screened into various size fractions prior to use, six sizes for the fine aggregate and four sizes for the coarse aggregate (Table 5). Aggregate batches were weighed in the air-dried condition and inundated with a known amount of water 18 to 20 hr. prior to use. Excess water was drawn off and weighed immediately prior to mixing. This procedure permitted the use of the aggregate in the resulting degree of saturation and provided a high degree of control over the total mixing water in a batch.

TABLE 1
CHEMICAL COMPOSITION OF CEMENTS
Chemical analyses of cements made in accordance with ASTM Standards current in May, 1949.

Cement Lot No.	Major Components—Percent							Minor Components—Percent					
	SiO_2	Al_2O_3	Fe_2O_3	Total CaO	MgO	SO_3	Ign. Loss	Mn_2O_3	Free CaO	Insol. Res.	Alkalies Na_2O	Alkalies K_2O	Alkalies Total as Na_2O
Type I Cements													
18266	21.74	6.06	2.21	62.17	2.61	2.51	1.15	0.10	0.82	0.28	0.15	1.14	0.90
18267	20.65	6.34	3.01	64.43	1.64	1.77	1.04	0.23	0.95	0.16	0.29	0.52	0.63
18268	20.47	6.88	2.85	63.14	2.24	1.98	1.30	0.73	0.73	0.14	0.12	0.18	0.24
18269[a]	20.95	6.43	2.69	63.25	2.16	2.09	1.16	0.35	0.83	0.19	0.19	0.61	0.59
Type IA Cements													
18270	21.77	5.90	2.29	62.47	2.73	2.28	1.10	0.10	0.50	0.22	0.14	1.07	0.84
18271	21.10	6.40	2.97	64.56	1.77	1.32	0.81	0.22	0.41	0.24	0.28	0.49	0.60
18272	20.52	6.61	2.83	63.32	2.52	2.10	1.17	0.62	0.69	0.23	0.11	0.17	0.22
18273[a]	21.13	6.30	2.70	63.45	2.34	1.90	1.03	0.31	0.53	0.23	0.18	0.58	0.56

[a] These are blends of the three individual brands of each type. The analyses indicated are the arithmetical averages of the analyses of the individual cements.

TABLE 2
POTENTIAL COMPOUND COMPOSITION OF CEMENTS

Cement Lot No.	Calculated Compound Composition—percent					
	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	Free CaO
Type I Cements						
18266	33.5	37.1	12.3	6.7	4.27	0.82
18267	49.5	21.9	11.7	9.2	3.01	0.95
18268	42.5	26.6	13.4	8.7	3.37	0.73
18269[a]	41.8	28.5	12.5	8.2	3.55	0.83
Type IA Cements						
18270	37.4	34.2	11.8	7.0	3.88	0.50
18271	49.7	23.0	11.9	9.0	2.24	0.41
18272	44.5	25.3	12.7	8.6	3.57	0.69
18273[a]	43.9	27.5	12.1	8.2	3.23	0.53

[a] Blends. Results are averages of individual cements.

FABRICATION OF SPECIMENS

Each batch mixed contained 1.10 cu. ft. of concrete. All batches were mixed for 3 minutes. For each particular concrete, three like

batches were prepared, each on a different day, containing sufficient concrete to make one 6- by 6- by 30-in. beam, one 3- by 3- by $11\frac{1}{4}$-in. prism and one 3- by 6- by 15-in. slab. A slump test and an air-content determination by the pressure method were made on each batch of concrete.

For the $5\frac{1}{2}$-sack-per-cu.-yd. concrete used in strength tests through one year, one 6- by 6- by 30-in. beam and one 6- by 12-in. cylinder were made from each of three duplicate batches of concrete made for each test age.

Beam, prism, and slab molds were filled in two equal layers, and each layer was rodded with a $\frac{5}{8}$-in.-diameter bullet-nose tamper, 63 roddings per layer for the beams, 25 per layer for the prisms and 50 per layer for the slabs. Immediately after casting, the surface of the prism was finished with a steel trowel, and the surfaces of the beam and slab were finished with a wood float. The cylinder molds were filled in three equal layers, and each layer was rodded 25 times. All molds were made of steel.

Specimens were covered with two layers of damp burlap and a tarpaulin. At age of 20 to 24 hr., the molds were stripped and the

TABLE 3
MISCELLANEOUS PHYSICAL TESTS OF CEMENTS

Tests made in accordance with ASTM Standards current in May, 1949. Each value is the average of two or more determinations.

Cement Lot No.	Fineness, Spec. Surface, sq. cm. per g., Wagner	Fineness, Spec. Surface, sq. cm. per g., Blaine	Fineness, Passing 325-Mesh	Specific Gravity	Normal Consistency, Percent	Time of Setting, Vicat Needle, Init., h m.	Time of Setting, Vicat Needle, Fin., h.m.	Time of Setting, Gillmore Needle, Init., h.m.	Time of Setting, Gillmore Needle, Fin., h.m.	Autoclave Expansion, Percent	Air Content, Percent 1–4 Mortar
Type I Cements											
18266	1750	3370	93.8	3.143	26.0	3.10	5:50	3:55	6:05	0.25	10.4
18267	1800	3220	93.0	3.149	25.5	3.35	6.05	4:05	6.10	0.25	9.9
18268	1790	3610	87.9	3.139	24.5	2.55	6.10	3:55	6.25	0.08	6.8
18269	1770	3370	91.6	3.140	26.0	3:25	6:00	4:15	6:20	0.18	8.9
Type IA Cements											
18270	1820	3440	94.2	3.145	26.0	3.40	5:55	4:30	6:20	0.26	17.9
18271	1900	3270	93.9	3.164	26.0	2:10	5.45	2:35	6:15	0.25	19.1
18272	1870	3610	90.1	3.134	28.0	4.15	7:30	5:30	7.40	0.12	18.4
18273	1860	3450	92.3	3.141	27.5	4.30	7:20	5:25	7:40	0.20	17.8

TABLE 4
STRENGTH TESTS OF MORTARS

Briquets ASTM C190-44. Cubes ASTM C109-47[a]
Each value is the average of three specimens, each made on a different day.

Cement Lot No	Tensile Strength, 1-3 Standard Sand Mortar Briquets, lb. per sq. in.					Compressive Strength, 2-in. Plastic Mortar Cubes, lb. per sq. in.				
	1 d.	3 d.	7 d.	28 d.	1 y.	1 d.	3 d	7 d.	28 d.	1 y.
Type I Cements										
18266	215	370	420	495	490	700	1750	2570	4190	5040
18267	155	365	425	525	480	420	1640	2880	4230	4770
18268	175	325	435	500	485	400	1330	2130	3950	4820
18269	200	300	410	495	495	500	1570	2490	4060	5050
Type IA Cements										
18270	230	370	430	480	470	560	1600	2370	3720	4510
18271	85	295	390	460	435	230	1410	2470	3850	4320
18272	160	310	390	480	455	465	1330	2040	3670	4660
18273	160	305	380	470	470	420	1520	2380	3930	4020

[a] These ASTM methods of test were in force at the time these tests were made.

specimens stored in the moistroom. Prior to being placed in the moist-room, the slabs were equipped with a 1:2 mortar dike, approximately ¾ by ¾ in. in section, around the edges of the finished surface.

CURING CONDITIONS

All strength specimens, beams and cylinders, were cured continuously moist until time for test. The prisms used in the freezing-and-thawing tests were cured 1 day in molds, 13 days in the moistroom, 14 days in air of the laboratory, and 3 days in water, prior to the start of tests. For the 4.0- and 7.0-sack-per-cu.-yd. concretes, additional prisms were prepared at a later date from repeat batches and cured 1 day in molds, 27* days in the moistroom, and 3 days in water.

The slabs were cured 1 day in molds, 13 days in the moistroom, 14 days in the air of the laboratory, and then 3 more days in air with a ⅜-in. layer of water maintained on the top surface.

TABLE 5
DATA ON AGGREGATES

Elgin, Illinois, Sand

Grading—percent Retained on Sieve No. Indicated: 4	8	16	30	50	100	Fineness Modulus	Bulk Specific Gravity S.S.D.[a]	24-hr. Absorption, percent by Wt.
0	18	33	57	87	95	2.90	2.645	2.25

Eau Claire, Wisconsin Gravel

Maximum Size of Aggregates, in.	Grading—percent Retained on Sieve Size Indicated					Bulk Specific Gravity S.S.D.[a]	24-hr. Absorption percent by Wt.
	2½-in	1½-in.	¾-in.	⅜-in.	No. 4		
2½	0	25	50	75	100	2.683	1.05
1½	0	0	50	75	100	2.702	1.04
¾	0	0	0	50	100	2.693	1.33
⅜	0	0	0	0	100	2.681	1.58

[a] Saturated, surface—dry.

TEST METHODS

Strength tests of beams and cylinders were conducted in accordance with applicable ASTM methods of test. The beams were tested in flexure using third-point loading over an 18-in. span, permitting two flexural breaks per beam. Compression tests were made using beam ends as 6-in. modified cubes.

Freezing-and-thawing tests were conducted on the prisms immersed in tap water at all times. Two complete cycles of freezing and thawing were obtained every 24 hr. The rate of cooling was approximately 20 F. per hr. Periodically during the tests determinations were made of changes in length, weight, and sonic modulus of elasticity.

The surface-scaling test consisted of freezing a ⅛-in. layer of water on the top surface of the slab and then thawing the ice with flake calcium chloride, applied in an amount equivalent to 2.4 lb. per sq. yd. of surface area. The slabs were subjected to one cycle of this procedure per day. The amount of scaling was determined by visual examination and rated numerically as follows:

0—no scale	2—slight to moderate	4—moderate to bad
1—slight	3—moderate	5—bad

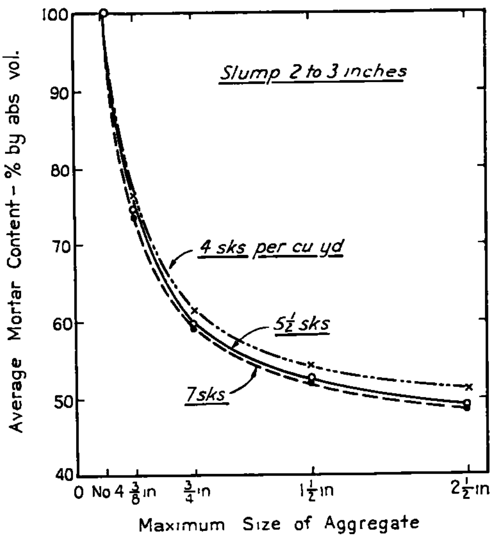

Figure 1. Relationship between maximum size of aggregate and mortar content for concretes of constant cement-content and consistency.

The middle section of each 6- by 6- by 30-in. beam was used for determinations of bubble spacing factors of air voids. These determinations were made by the linear traverse method.[1]

DISCUSSION OF RESULTS

Characteristics of Concrete Mixes—The data on the concrete mixes used in this investiga-

[1] L. S. Brown and C. U. Pierson, "Linear Traverse Technique for Measurement of Air in Hardened Concrete," ACI *Proceedings* Vol. 47, October, 1950.

tion are shown in Tables 6, 7 and 8. Changing the maximum size of aggregate in a concrete mix while maintaining the cement content and consistency constant results in a change in the mortar content of the concrete. Figure 1 shows the variation in average mortar content with maximum size of aggregate for the three cement-contents used in this study.

The variations in air content with maximum size of aggregate are shown in Figure 2, along with the average mortar contents. The concrete air-contents are approximately proportional to the mortar contents, which accounts for the rapid increase in air content for aggregate size below ¾ in.

Figure 3 shows the effect of entrained air on the water requirements of these concretes made with various maximum sizes of aggregate. The reduction in water with entrained air is more pronounced in the leaner mixes. For example, with 2½-in.-top-size aggregate, the reduction in water for the 4-sack mix was 1¾ gal. per sack, while for the 7-sack mix the reduction was less than ¼ gal. per sack. For a particular cement content, the entrainment of air resulted in increasingly larger reductions in water requirements as the maximum size of aggregate decreased.

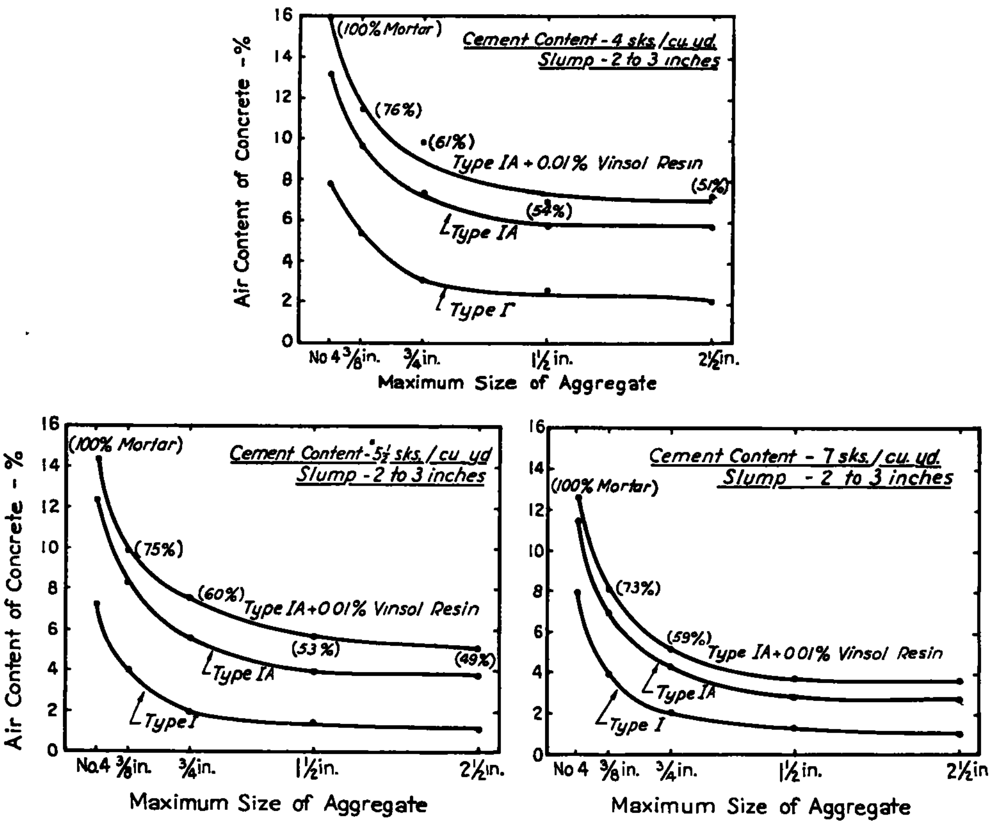

Figure 2. Relationship between maximum size of aggregate and air content for concretes of constant cement-content and consistency.

Effect of Entrained Air on Concrete Strengths—The results of flexural and compressive strength tests of 6- by 6- by 30-in. beams cured continuously moist for 28 days are shown in Tables 6, 7, and 8 and in Figures 4, 5, and 6.

For a given cement content, the effect of entrained air on both flexural and compressive strength is compensated to a considerable degree by the decrease in water content with increased air content. For instance, in the 4-sack-per-cu.-yd. mixes, particularly those

made with maximum size of aggregate ¾ in. or smaller, the reduction in water with entrainment of air was large enough to result in increases in strength. In the 7-sack-per-cu.-yd. mixes, the entrainment of air was generally accompanied by a reduction in both flexural and compressive strengths. The reductions in water content in these mixes were insufficient, despite the use of less sand with increased air contents, to offset entirely the effect of the entrained air on strength. However, it should be noted that in order better to establish trends, the maximum air contents used in these tests were well above those which would ordinarily be used in practice for corresponding concretes. Thus, the maximum reductions in strength shown in Figures 4, 5 and 6 are larger than those to be expected in practice where the air content is under good control.

Table 9 summarizes the results of these 28-day strength tests in showing the average percentage change in strength for each 1 percent of intentionally entrained air up to 6 percent. (Intentionally entrained air is defined as that portion of air entrained in addition to the amount entrained with the Type I cement alone.) These percentage changes in strength are calculated from the average air-content-and-strength relationships shown in Figures 4, 5, and 6, using the strength of the non-air-entrained concrete in each group as the reference strength. For constant cement content and consistency, the reduction in strength with entrainment of air decreases

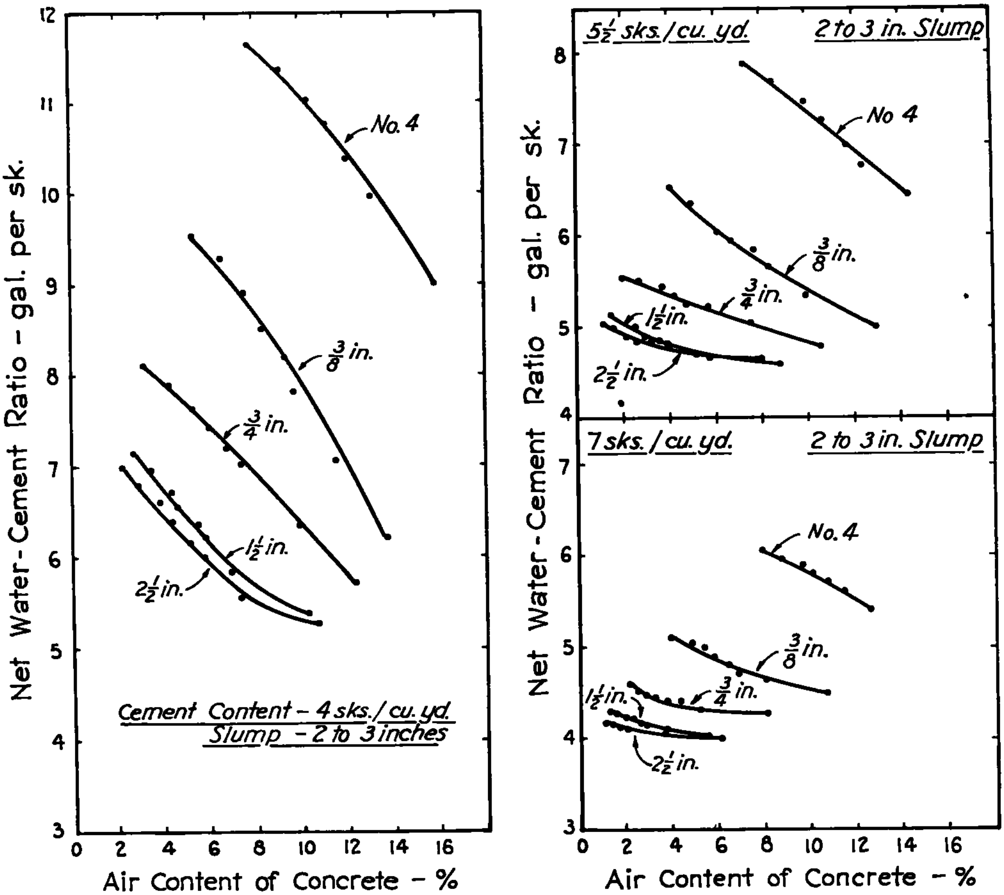

Figure 3. Effect of air content on the water requirement of concretes of constant cement-content and consistency made with various maximum sizes of aggregate.

as the maximum size of aggregate decreases, due to the previously mentioned larger reductions in water requirements for concretes made with the smaller-size aggregates.

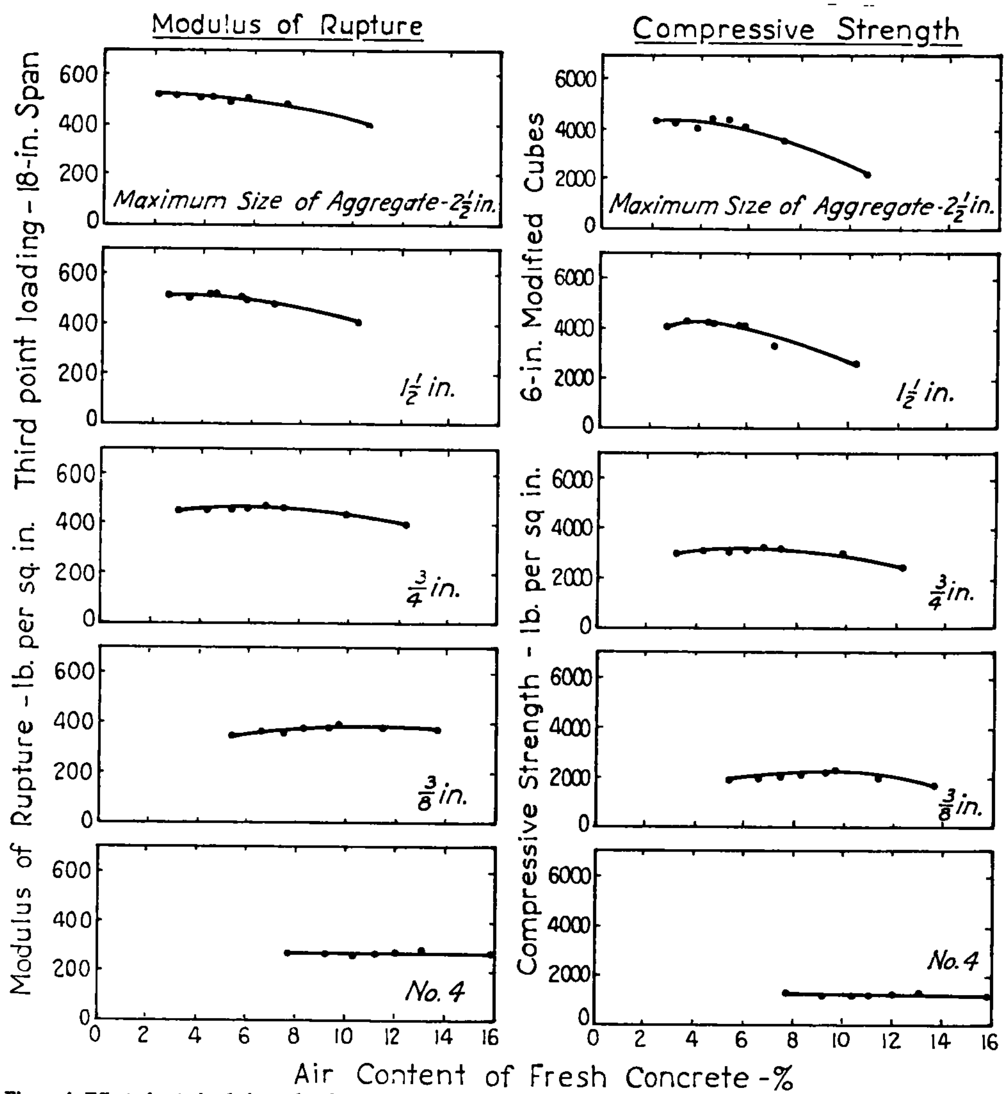

Figure 4. Effect of entrained air on the 28-day strengths of concretes of constant cement-content and consistency made with various maximum sizes of aggregate.

The results of strength tests through one year, shown in Table 10 and Figure 7, indicate that the effect of entrained air on strength changes little with age. These tests afforded also a comparison between compressive strenghts of 6-in. modified cubes and companion 6- by 12-in. cylinders. This relationship is shown in Figure 8. For these concretes, the two different specimen sizes and shapes showed approximately equal compressive strengths. Other tests made with different cements and aggregates have indicated that the 6-in. modified cubes give somewhat higher compressive strengths than the 6- by 12-in. cylinders.

Effect of Entrained Air on Length and Weight Changes of Concrete During Curing—Length

and weight changes of 3- by 3- by 11¼-in. concrete prisms were determined during the curing period consisting of 14 days moist, 14 days in the air of the laboratory, and 3 days initial 14 days of moist storage, a trend toward increased contraction with increase in air content during the following 14 days in air, and a slight trend toward increased expansion

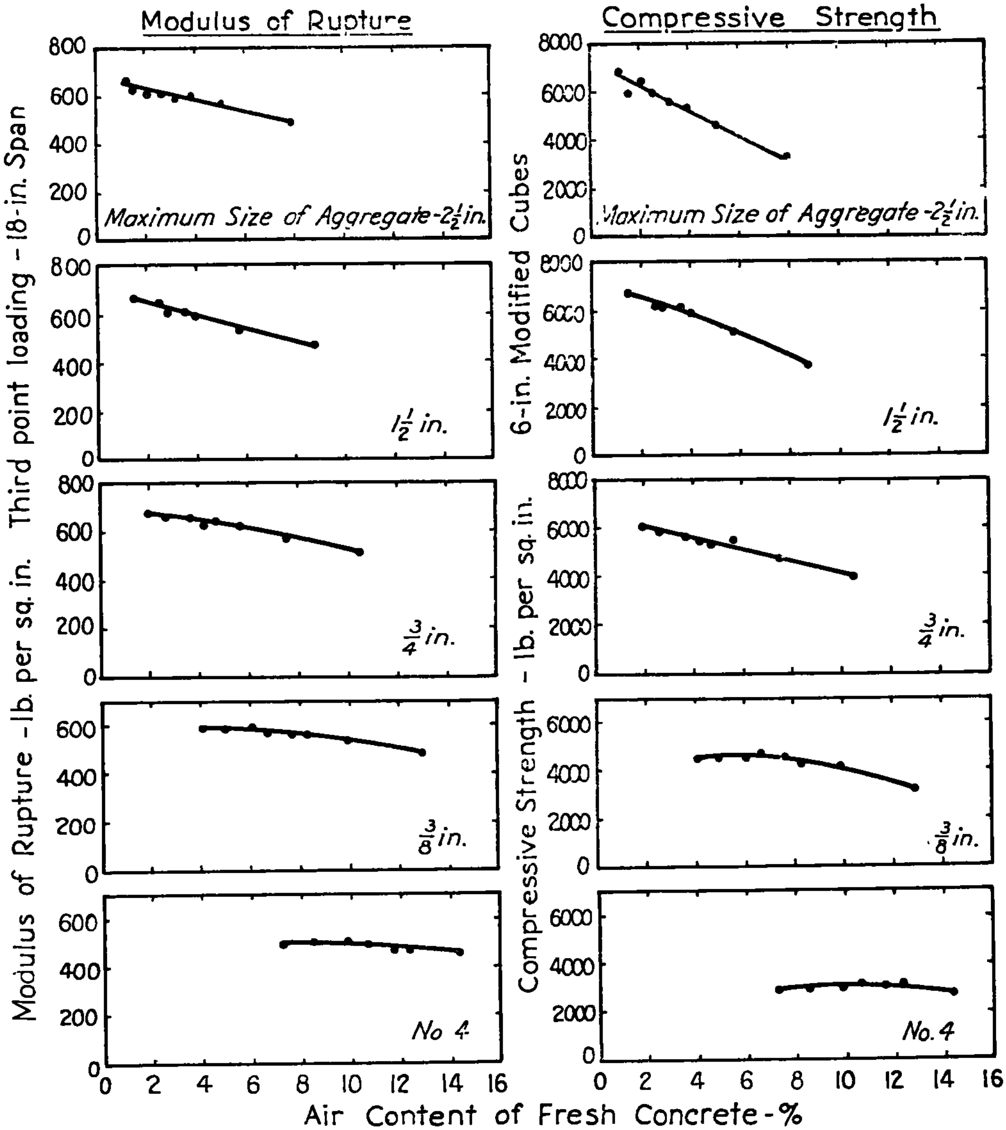

Figure 5. Effect of entrained air on the 28-day strengths of concretes of constant cement-content and consistency made with various maximum sizes of aggregate.

in water, prior to the start of freezing-and-thawing tests. These data are shown in Tables 11, 12, and 13.

There appears to be no significant effect of entrained air on the length changes during the with increase in air content during the 3 days storage in water. However, the differences noted were relatively small, particularly for the 5½- and 7-sack mixes.

During the initial 14 days of moist storage,

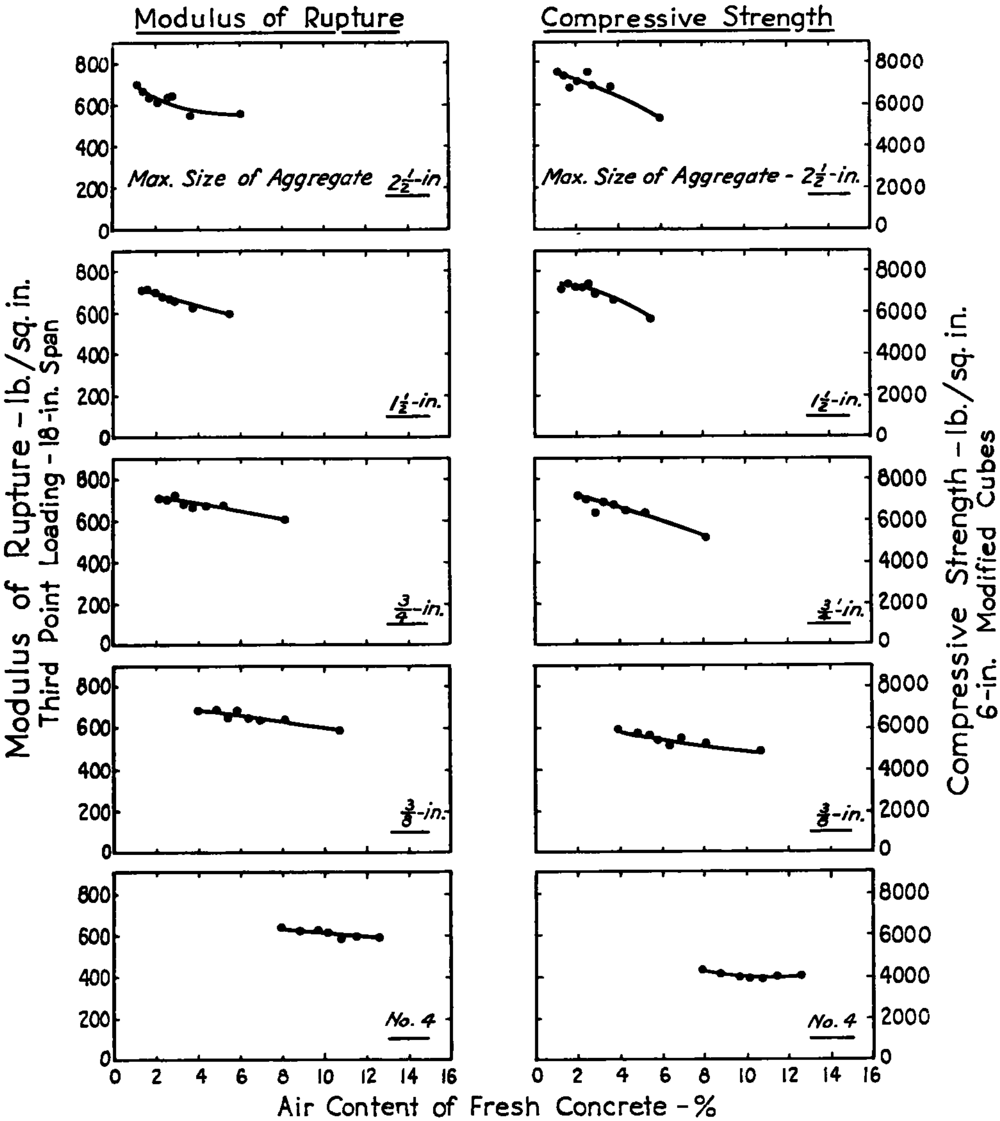

Figure 6. Effect of entrained air on the 28-day strengths of concretes of constant cement-content and consistency made with various maximum sizes of aggregate.

the 4-sack-per-cu.-yd. concretes showed increasing weight gains with increase in air contents, while for the 5½- and 7-sack concretes the changes in weight did not vary with air content. During the 14 days in the air of the laboratory, none of the concretes showed any significant differences in loss of water with air content. The absorptions, as measured by the changes in weight during the 3-day water-storage period, show no significant effect of air content.

Entrained Air on Resistance to Freezing and Thawing of Concretes—Freezing-and-thawing tests were made on 3- by 3- by 11¼-in. concrete prisms immersed in tap water. Two cycles of freezing and thawing were obtained every 24 hr. All of the concretes were 31 days old at the start of the tests.

Tables 14, 15, and 16 show the expansions, changes in dynamic modulus, and changes in weight during 300 cycles of freezing and thawing. In addition, where available, the number

TABLE 6

CONCRETE MIX DATA AND 28-DAY MOIST-CURED STRENGTHS—4 SACKS PER CU. YD.

Concrete specimens: 6 x 6 x 30-in. beams. Elgin, Ill. sand and Eau Claire, Wis. gravel.
Cement content of all concretes—4 sk. per cu. yd. Slump—2 to 3 in.
Type I Cement—Lot 18269 Type IA Cement—Lot 18273.
Each strength value is the average of tests of three specimens, two flexural tests and two compressive tests per specimen.

Ref. No.	Percentage of Each Type Used		Net W/C, gal. per sk.	Slump, in.	Percent Sand, by Abs. vol.	Mortar Content, Percent by Abs. Volume	Air Content, Percent Pressure Method	28 d. Strength—lb. per sq. in.	
	I	IA						Mod. of Rupture, 3rd pt. Loading 18-in. Span	Compressive Strength, 6-in. Modified Cubes
Maximum Size of Aggregate—2½ in.									
78	100	0	6.98	2.5	37.9	52.2	2.13	520	4380
79	80	20	6.80	3.0	37.3	52.0	2.91	515	4260
80	60	40	6.61	2.9	36.5	51.7	3.80	505	4060
81	45	55	6.39	2.7	36.0	51.4	4.36	510	4410
82	25	75	6.16	2.6	35.0	50.8	5.04	485	4400
83	0	100	6.00	2.4	34.5	50.7	5.77	510	4130
84	0	100[a]	5.55	2.2	33.0	50.0	7.28	485	3570
85	0	100[a]	5.28	2.6	30.0	49.7	10.62	400	2290
Maximum Size of Agrgegate—1½ in.									
86	100	0	7.14	2.1	42.2	56.0	2.63	515	4080
87	80	20	6.96	2.2	41.2	55.5	3.44	505	4340
88	60	40	6.72	2.5	40.2	54.9	4.28	520	4260
89	45	55	6.54	2.2	39.6	54.6	4.57	520	4210
90	25	75	6.36	2.2	38.9	54.3	5.54	510	4140
91	0	100	6.22	2.5	38.2	53.8	5.79	495	4140
92	0	100[a]	5.84	2.1	36.7	52.9	6.94	480	3360
93	0	100[a]	5.38	2.1	34.1	52.6	10.23	410	2640
Maximum Size of Aggregate—¾ in.									
94	100	0	8.12	2.2	50.0	63.1	3.11	450	3000
95	80	20	7.89	2.1	49.0	62.7	4.21	455	3190
96	60	40	7.64	2.6	48.0	62.2	5.25	455	3080
97	45	55	7.42	2.5	47.1	61.7	5.96	460	3190
98	25	75	7.20	2.7	46.0	61.2	6.65	475	3320
99	0	100	7.02	2.8	45.5	61.0	7.35	460	3200
100	0	100[a]	6.35	2.8	43.4	60.2	9.86	440	3020
101	0	100[a]	5.72	2.5	41.0	59.3	12.24	400	2550
Maximum Size of Aggregate—⅜ in.									
102	100	0	9.53	2.0	68.8	78.6	5.38	345	1870
103	80	20	9.28	2.1	67.9	78.2	6.58	365	2000
104	60	40	8.91	2.5	66.8	77.5	7.47	355	2040
105	45	55	8.52	2.2	65.9	76.9	8.28	375	2160
106	25	75	8.20	2.4	64.8	76.3	9.25	380	2260
107	0	100	7.81	2.1	63.9	75.6	9.61	395	2370
108	0	100[a]	7.05	2.4	61.9	74.3	11.43	380	2000
109	0	100[a]	6.21	2.7	59.3	72.8	13.65	370	1770
Maximum Size of Aggregate—No. 4 Mesh									
110	100	0	11.62	1.8	100	100	7.80	270	1280
111	80	20	11.35	2.0	100	100	9.18	265	1220
112	60	40	11.02	2.3	100	100	10.33	265	1210
113	45	55	10.75	2.3	100	100	11.18	275	1230
114	25	75	10.38	2.6	100	100	12.04	270	1280
115	0	100	9.97	2.4	100	100	13.13	280	1320
116	0	100[a]	9.00	2.3	100	100	15.85	275	1310

[a] Neutralized Vinsol resin in solution added at the mixer to entrain additional air.

of cycles for 0.10 percent expansion is also shown. Where the specimens have not yet reached 0.10 percent expansion, the latest available expansion data are presented.

All of these criteria indicate the steady increase in resistance to freezing and thawing with increases in the amount of entrained air. For example, in the 5½-sack concrete made with aggregate of 2½-in. maximum size, the concrete made with Type I cement (Ref.

TABLE 7

CONCRETE MIX DATA AND 28-DAY MOIST-CURED STRENGTHS—5½ SACKS PER CU. YD.

Concrete specimens: 6 x 6 x 30-in. beams. Elgin, Ill. sand and Eau Claire, Wis. gravel.
Cement content of all concretes—5½ sk. per cu. yd. Slump—2 to 3 in.
Type I Cement—Lot No. 18268. Type IA Cement—Lot 18273.
Each strength value is the average of tests of three specimens, two flexural tests and two compressive tests per specimen.

Ref. No.	Percentage of Each Type Used		Net W/C, gal. per sk.	Slump, in.	Percent Sand, by Abs. Vol	Mortar Content, percent by Abs. Volume	Air Content, Percent Pressure Method	28 d Strength—lb. per sq. in.	
	I	IA						Mod. of Rupture, 3rd. pt Loading 18-in. Span	Compressive Strength, 6-in. Modified Cubes
					Maximum Size of Aggregate—2½ in.				
31	100	0	5.04	2.8	33.0	49.2	1.14	665	6800
32	80	20	4.99	2.6	33.0	49.5	1.52	625	5900
33	60	40	4.88	2.3	32.0	48.9	2.07	610	6400
34	45	55	4.84	2.4	32.0	49.1	2.55	610	5920
35	25	75	4.85	2.5	31.0	48.9	3.20	585	5550
36	0	100	4.82	2.7	31.0	49.2	3.89	600	5300
37	0	100[a]	4.69	2.4	29.0	48.5	5.11	565	4600
38	0	100[a]	4.64	2.5	27.0	49.0	7.98	485	3300
					Maximum Size of Aggregate—1½ in.				
1	100	0	5.13	2.7	38.0	53.8	1.43	665	6680
2	60	40	5.01	2.8	37.0	54.0	2.51	650	6180
3	45	55	4.89	2.2	36.0	52.8	2.86	605	6100
4	25	75	4.85	2.4	35.0	52.4	3.55	610	6130
5	0	100	4.78	2.1	34.0	51.8	3.99	595	5860
6	0	100[a]	4.67	2.2	33.0	52.1	5.72	535	5030
7	0	100[a]	4.58	2.2	30.0	52.1	8.76	470	3700
					Maximum Size of Aggregate—¾ in.				
8	100	0	5.54	2.1	46.0	60.6	1.98	680	6020
9	80	20	5.51	2.6	45.5	60.5	2.66	660	5860
10	60	40	5.44	3.0	45.0	60.5	3.68	660	5600
11	45	55	5.35	2.9	44.0	60.0	4.21	630	5410
12	25	75	5.25	2.6	43.0	59.5	4.69	640	5280
13	0	100	5.23	3.1	42.0	59.3	5.63	625	5410
14	0	100[a]	5.04	2.8	41.0	59.4	7.53	570	4700
15	0	100[a]	4.78	2.6	38.0	58.9	10.49	515	3950
					Maximum Size of Aggregate—⅜ in.				
16	100	0	6.51	2.0	65.0	75.9	4.05	585	4430
17	80	20	6.36	2.9	64.5	75.9	4.99	585	4460
18	60	40	6.04	2.1	64.0	75.6	6.06	590	4460
19	45	55	5.96	2.6	63.0	75.0	6.66	570	4630
20	25	75	5.85	3.1	62.0	74.6	7.64	560	4500
21	0	100	5.67	2.8	61.0	74.0	8.30	555	4200
22	0	100[a]	5.35	2.3	59.0	73.0	9.89	535	4130
23	0	100[a]	5.01	2.4	56.0	72.0	12.88	480	3180
					Maximum Size of Aggregate—No. 4 Mesh				
24	100	0	7.88	1.8	100	100	7.25	490	2820
25	80	20	7.69	2.2	100	100	8.49	500	2910
26	60	40	7.47	2.7	100	100	9.84	500	2930
27	45	55	7.26	2.5	100	100	10.62	490	3120
28	25	75	6.99	1.9	100	100	11.65	465	3010
29	0	100	6.76	1.9	100	100	12.33	465	3100
30	0	100[a]	6.45	2.5	100	100	14.33	455	2680

[a] Neutralized Vinsol resin in solution added at the mixer to entrain additional air.

No. 31) reached 0.10 percent expansion in 63 cycles whereas the concrete made with the Type IA cement (Ref. No. 36) withstood 697 cycles before reaching this same expansion, more than a ten-fold increase in durability. Approximately the same increase in durability can be noted for all of the concretes made with Type IA cement included in this investigation.

Figure 9 shows the expansions of the concretes during 300 cycles of freezing and

TABLE 8

CONCRETE MIX DATA AND 28-DAY MOIST-CURED STRENGTHS—7 SACKS PER CU. YD.

Concrete specimens: 6 x 6 x 30-in. beams. Elgin, Ill. sand and Eau Claire, Wis. gravel.
Cement content of all concretes—7 sk. per cu. yd. Slump—2 to 3 in.
Type I Cement—Lot 18269. Type IA Cement—Lot 18273.
Each strength value is the average of tests of three specimens, two flexural tests and two compressive tests per specimen.

Ref. No.	Percentage of Each Type Used		Net W/C, gal. per sk.	Slump, in.	Percent Sand, by Abs. Vol.	Mortar Content, Percent by Abs. Volume	Air Content, Percent Pressure Method	28 d. Strength—lb. per sq. in.	
	I	IA						Mod. of Rupture, 3rd Pt. Loading 18-in. Span	Compressive Strength, 6-in. Modified Cubes
Maximum Size of Aggregate—2½ in.									
39	100	0	4.16	2.5	29.5	49.1	1.12	700	7570
40	80	20	4.14	2.3	29.0	48.9	1.40	665	7350
41	60	40	4.12	2.5	28.5	48.7	1.73	635	6780
42	45	55	4.10	2.0	28.0	48.6	2.04	615	7040
43	25	75	4.11	2.6	27.5	48.7	2.59	640	7530
44	0	100	4.10	2.5	27.0	48.5	2.77	650	6920
45	0	100[a]	4.04	2.3	25.5	47.9	3.65	550	6810
46	0	100[a]	4.00	2.3	24.0	48.3	6.05	560	5390
Maximum Size of Aggregate—1½ in.									
47	100	0	4.28	2.2	34.0	52.9	1.31	705	7110
48	80	20	4.26	2.3	33.5	52.8	1.60	710	7360
49	60	40	4.22	2.0	33.0	52.6	1.99	700	7180
50	45	55	4.21	2.4	32.0	52.1	2.28	675	7170
51	25	75	4.16	2.0	31.0	51.5	2.60	665	7370
52	0	100	4.13	1.9	30.0	51.0	2.87	655	6850
53	0	100[a]	4.10	2.0	28.5	50.6	3.77	625	6530
54	0	100[a]	4.02	1.9	27.0	50.6	5.51	595	5670
Maximum Size of Aggregate—¾ in.									
55	100	0	4.58	2.5	42.0	59.6	2.10	710	7120
56	80	20	4.51	2.3	41.5	59.3	2.46	700	7010
57	60	40	4.46	2.2	41.0	59.1	2.89	720	6360
58	45	55	4.44	2.2	41.0	59.3	3.26	680	6860
59	25	75	4.42	2.1	40.5	59.1	3.76	665	6730
60	0	100	4.41	2.2	40.0	59.2	4.34	675	6410
61	0	100[a]	4.31	2.0	39.0	58.8	5.20	675	6360
62	0	100[a]	4.27	2.4	37.5	59.3	8.08	605	5180
Maximum Size of Aggregate—⅜ In.									
63	100	0	5.10	2.9	61.0	74.2	3.94	685	5880
64	80	20	5.04	2.6	60.5	74.1	4.82	690	5760
65	60	40	4.99	3.0	60.0	73.9	5.40	655	5660
66	45	55	4.89	2.5	59.0	73.4	5.81	685	5400
67	25	75	4.80	2.9	58.5	73.1	6.39	650	5150
68	0	100	4.71	2.5	58.0	72.9	6.88	640	5520
69	0	100[a]	4.63	2.4	57.0	72.7	8.07	640	5280
70	0	100[a]	4.49	2.7	55.5	72.5	10.74	590	4880
Maximum Size of Aggregate—No. 4 Mesh									
71	100	0	6.04	2.3	100	100	7.90	635	4320
72	80	20	5.96	2.4	100	100	8.77	620	4080
73	60	40	5.90	2.8	100	100	9.66	620	3940
74	45	55	5.81	2.8	100	100	10.10	610	3940
75	25	75	5.70	2.6	100	100	10.76	580	3880
76	0	100	5.61	2.6	100	100	11.42	590	3990
77	0	100[a]	5.40	2.2	100	100	12.56	590	4040

[a] Neutralized Vinsol resin in solution added at the mixer to entrain additional air.

thawing. These data indicate that the optimum air content for these concretes, insofar as resistance to freezing and thawing is concerned, increased as the maximum size of aggregate decreased, the optimum air content considered to be that minimum air content beyond which further increases in air result in only a marginal decrease in expan-

sion. This air content is optimum in the sense that it is, in general, a balance point between increase in durability and reduction in strength. These optimum concrete air contents determined visually from Figure 9 are shown in Table 17. The optimum concrete air contents differ only slightly with changes in cement content for a particular maximum size of aggregate. These differences appear too small to be of any significance.

changes in water-cement ratio, while the calculated mortar air contents remain approximately constant. The paste air requirements increase with an increase in water-cement ratio. The method used to calculate the air contents of the mortar and paste fractions is shown in Table 17.

The data imply that for a particular consistency, concrete which will undergo some drying prior to exposure to frost action can be made resistant to freezing and thawing by providing a relatively constant air content in the mortar fraction, regardless of cement content or maximum size of aggregate, with the two exceptions mentioned previously. It appears that those concretes in this study having 9 ± 1 percent air in the mortar fraction and subjected to some drying during the curing period showed excellent resistance to freezing and thawing. A change in the concrete consistency from that used in this study or a change in aggregate type might necessitate a change in the required amount of air in the mortar fraction. Only one consistency, one sand, and one coarse aggregate were used in

TABLE 9

EFFECT OF ENTRAINED AIR ON CONCRETE STRENGTHS

Flexure: 6 by 6 by 30-in. beams. Third-point loading, 18-in. span. Two breaks per beam.
Compression 6-in. modified cubes. Two cubes per beam.
Age at test. 28 days. Curing: Continuously moist.
Data obtained by averaging results of tests on three like specimens.

Maximum Size of Aggregate	Average Percentage Change in Strength for Each 1 Percent of Entrained Air for Total Amounts of Entrained Air Shown											
	Flexure						Compression					
	1%	2%	3%	4%	5%	6%	1%	2%	3%	4%	5%	6%
	4 Sk. per Cu. Yd.—2 to 3-in. Slump											
2½-in.	−1.0	−1.0	−1.3	−1.6	−1.9	−2.1	0	−1.2	−1.9	−2.6	−3.2	−3.8
1½-in.	0	−0.5	−1.0	−1 2	−1.7	−2.1	+3.7	+1.5	−0.4	−1.8	−3.2	−4.1
¾-in.	+2.2	+1 7	+1.5	+1.1	+0.4	0	+5.0	+3 4	+2.2	+1 7	+1.0	0
⅜-in.	+4.3	+3.6	+3.4	+2.6	+2.0	+1.7	+9.6	+7.5	+5.9	+4.4	+3.5	+2.1
No. 4	0	0	0	0	0	0	0	0	0	0	0	0
	5½ Sk. per Cu. Yd.—2 to 3-in. Slump											
2½-in.	−3.8	−3.4	−3.6	−3.6	−3.7	−3.8	−7.5	−7.5	−7.5	−7.5	−7.6	−7.7
1½-in.	−3.8	−3.8	−4.0	−4.0	−4.0	−4 0	−5 0	−5.0	−5.3	−5.5	−5.8	−6.0
¾-in.	−2.9	−2.6	−2.7	−2.6	−2.6	−2.7	−3 3	−3.3	−3.6	−3.8	−3.8	−3.9
⅜-in.	−0.9	−0 9	−1.1	−1.3	−1.5	−1 7	0	0	−0 4	−0.8	−1.3	−2.0
No. 4	+1.0	+1.0	+0.3	−0.1	−0.4	−0.9	+3 6	+3.6	+2.4	+1 8	+1 1	+0.3
	7 Sk. per Cu. Yd.—2 to 3-in. Slump											
2½-in.	−8.6	−7.2	−6.0	−5.0	−4.1	—	−4.0	−4.3	−4.9	−5.3	−5.7	—
1½-in	−3.5	−3 2	−3.5	−3 7	—	—	−1.4	−2.8	−4.1	−5.0	—	—
¾-in.	−1.4	−1.6	−1.9	−2.1	−2.2	−2.4	−2.8	−3.4	−3.3	−3.9	−4.2	−4.5
⅜-in.	−1.5	−1.5	−1.5	−1.7	−1.9	−1.9	−3.0	−2.8	−2.7	−2.6	−2 8	−2.7
No. 4	−1.6	−1.6	−1.6	−1.5	—	—	−5.1	−3.7	−2.7	−1.8	—	—

For these concretes of optimum air content, the calculated air contents of the mortar fractions, shown in Table 17, are approximately equal, except for the 4-sack concretes made with No. 4 and ⅜-in. maximum-size aggregates. This appears to be the result of a fortuitous combination of circumstances, and it is not believed that this should be regarded as necessarily having any fundamental significance. It is more probable that the amount of air per unit of paste has some theoretical significance with regard to resistance to frost action. However, as shown in Table 17, calculated paste air contents for these optimum concretes appear to be affected appreciably by

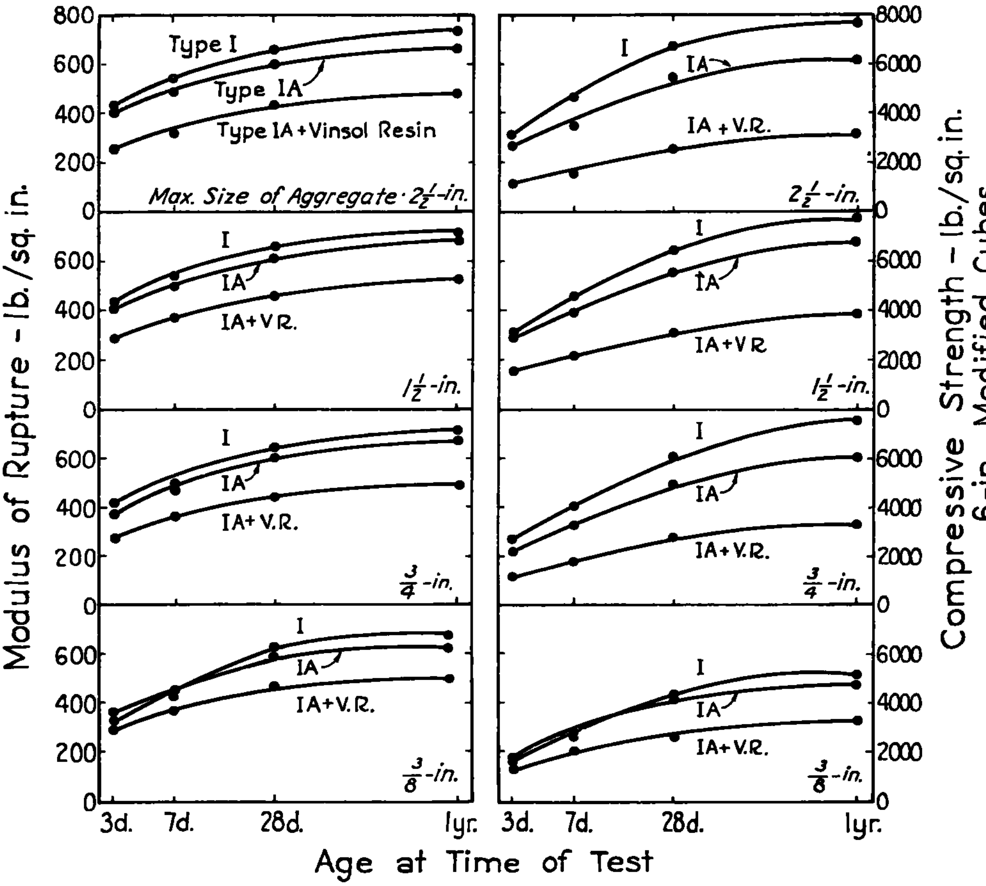

Figure 7. Age-strength relationships for concretes of constant cement-content and consistency made with various maximum sizes of aggregate.

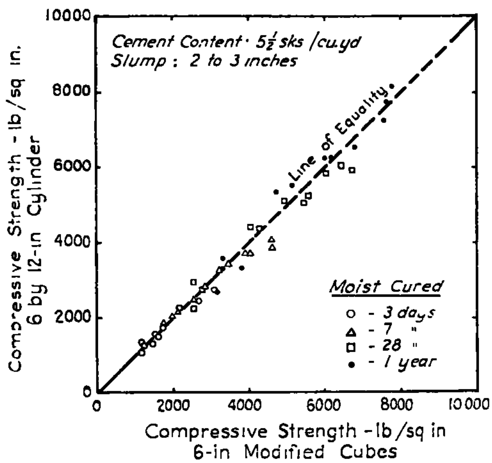

Figure 8. Relationship between strengths of 6-in. modified cubes and 6- by 12-in. cylinders for concretes of constant cement-content and consistency.

these tests. However, both field and laboratory experience with air-entrained concretes indicates that the resulting change would be relatively small. Changes in curing procedure appear to influence this air requirement.

Entrained Air on Resistance to Freezing and Thawing of Concrete Cured Continuously Moist—For the 4-sack and 7-sack concretes, additional specimens were prepared and cured 1 day in molds, 27 days in the moistroom, and 3 days in water, prior to the start of freezing and thawing tests. Figure 10 shows the expansions of these concretes during 300 cycles of freezing and thawing.

As was the case with the similar concretes whose curing included a period of air-drying, the data indicate a steady increase in resistance to freezing and thawing with increase in

entrained air. However, these concretes which were cured continuously moist were not as resistant to freezing and thawing as the concretes subjected to an air-drying period, except for the 7-sack concretes made with 2½-in., 1½-in., and ¾-in. maximum-size aggregates, which showed about the same resistance. For these exceptions, the criterion of 9 percent air in the mortar fraction indicated optimum air contents essentially the same as those for the similar air-dried concretes. For the remaining concretes which were continuously moist cured, the necessary amount of air to insure adequate durability was higher than for the concretes subjected to an air-drying period. No 5½-sack continuously moist-cured concretes were included in these tests.

Role of Type IA Cement in Providing Optimum Air Contents—The freezing-and-thawing data presented clearly indicate the different requirements for concrete air-content with changes in mortar content resulting from the use of different maximum sizes of coarse aggregate. In these tests, regardless of cement content or maximum size of aggregate, the use of the Type IA cement met to a large extent these demands for different air requirements which

TABLE 10

FLEXURAL AND COMPRESSIVE STRENGTHS OF CONCRETES—5½ SACKS PER CU. YD.

Specimens: 6- by 6- by 30-in. beams and 6- by 12-in. cylinders cured continuously moist.
Cement content. 5 and one-half sacks per cu. yd. Nominal slump: 2 to 3 in.
Elgin, Illinois, sand and Eau Claire, Wis., gravel.
Beams tested in third-point loading on an 18-in. span.

Cement Type	Air Content Percent Pressure	Modulus of Rupture lb. per sq. in.				Compressive Strengths—lb. per sq. in.							
						6-in. Modified Cubes				6- by 12-in. Cylinders			
		3 d.	7 d.	28 d.	1 yr.	3 d.	7 d.	28 d.	1 y.	3 d.	7 d.	28 d.	1 y.
Maximum Size of Aggregate—2½ in.													
I	1.15	435	545	660	735	3100	4620	6730	7650	2730	3880	5910	7730
IA	4.17	405	485	605	660	2640	3480	5480	6170	2450	3410	5060	6230
IA[a]	9.76	255	320	435	480	1180	1540	2550	3190	1040	1560	2220	2670
Maximum Size of Aggregate—1½ in.													
I	1.58	435	540	660	720	3090	4600	6430	7780	2750	4090	6050	8140
IA	4.02	405	495	615	685	2880	3900	5560	6800	2710	3700	5230	6510
IA[a]	8.63	285	370	460	525	1470	2140	3060	3830	1290	2150	2710	3300
Maximum Size of Aggregate—¾ in.													
I	2.16	415	500	645	715	2670	4030	6010	7580	2410	3700	5840	7220
IA	5.96	375	465	600	655	2180	3220	4940	6010	2250	3290	5100	6220
IA[a]	11.38	275	365	440	490	1190	1750	2790	3300	1340	1890	2750	3290
Maximum Size of Aggregate—⅜ in.													
I	4.14	325	425	625	675	1600	2560	4310	5170	1490	2500	4330	5510
IA	8.24	360	450	590	620	1730	2810	4060	4740	1730	2810	4380	5320
IA[a]	12 89	285	365	465	495	1250	2000	2590	3310	1270	2020	2940	3560

[a] Neutralized Vinsol resin added in solution at the mixer to entrain additional air.

TABLE 10A

Maximum Size of Aggregate	Optimum Concrete Air	Air Content of Concrete With type IA Cement
Cement Content—4 sk. per cu. yd.		
	%	%
2½-in.	4.5	5.8
1½-in.	4.5	5.8
¾-in.	5.5	7.4
⅜-in.	8.5	9.6
No. 4	12.5	13.1
Cement Content—5½ sk. per cu. yd.		
2½-in.	4.5	3.9
1½-in.	4.5	4.0
¾-in.	5.0	5.6
⅜-in.	6.5	8.3
No. 4	9.0	12.3
Cement Content—7 sk. per cu. yd.		
2½-in.	4.5	2.8
1½-in.	4.5	2.9
¾-in.	5.5	4.3
⅜-in.	7.0	6.9
No. 4	10.0	11.4

TABLE 11

LENGTH AND WEIGHT CHANGES OF CONCRETES PRIOR TO FREEZING AND THAWING

4 sacks per cu. yd.; 2- to 3-in. slump; 3- by 3- by 11¼-in. prisms.

Ref. No.	Net W/C, gal. per sk.	Air Content, Percent (Pressure)	Length Changes During Periods Indicated—Percent			Weight Changes During Periods Indicated—Percent		
			14 d. Moist (+)	14 d. Air (−)	3 d. in Water (+)	14 d. Moist (+)	14 d. Air (−)	3 d. in Water (+)
Maximum Size of Aggregate—2½ in.								
78	6.98	2.13	.006	.033	.021	0.5	3.2	2.7
79	6.80	2.91	.010	.036	.025	0.5	3.1	2.6
80	6.61	3.80	.009	.034	.024	0.6	3.0	2.7
81	6.39	4.36	.007	.038	.025	0.7	3.0	2.6
82	6.16	5.04	.009	.036	.025	0.7	2.9	2.5
83	6.00	5.77	.004	.036	.024	0.7	2.9	2.5
84	5.55	7.28	.010	.036	.026	0 9	2.8	2.3
85	5.28	10.62	.009	.037	026	1.3	3.2	2.4
Maximum Size of Aggregate—1½ in.								
86	7.14	2.63	.009	.034	.024	0.6	3.1	2.7
87	6 96	3.44	.007	.035	024	0.6	3.1	2.6
88	6 72	4.28	.004	.037	024	0.6	3.1	2.6
89	6.54	4.57	.008	.036	.025	0.7	3.0	2.5
90	6.36	5.54	.007	.035	.024	0.8	2.9	2.5
91	6.22	5.79	.009	.038	.026	0.8	2.9	2.5
92	5.84	6 94	.008	.036	.025	0.9	2.8	2.3
93	5.38	10.23	.006	.038	.026	1.1	2.8	2.2
Maximum Size of Aggregate—¾ in.								
94	8.12	3.11	.006	.037	.025	0.7	3.9	3.4
95	7.89	4.21	.005	.039	.025	0.7	4 0	3.4
96	7 64	5.25	.007	.041	.026	0.8	4.0	3.4
97	7.42	5.96	.003	.039	.026	0.8	3.8	3.2
98	7.20	6.65	.007	.041	.027	0.9	3.7	3.2
99	7.02	7.35	.006	.044	.028	1.0	3.7	3.1
100	6.35	9 86	.008	.043	.028	1.2	3.5	2.9
101	5.72	12.24	.004	.047	.030	1.5	3.4	2.6
Maximum Size of Aggregate—⅜ in.								
102	9.53	5.38	.004	.045	.031	0.9	5.6	5.1
103	9 28	6.58	.013	.046	033	0.9	5.5	5.0
104	8.91	7.47	.010	.049	.033	1.0	5.4	4.9
105	8 52	8.28	013	.048	.031	1.0	5.2	4 6
106	8.20	9.25	.011	.048	.031	1.1	5.0	4 4
107	7.81	9.61	.002	.048	.032	1.1	4.7	4 2
108	7.05	11.43	.008	.052	.032	1.4	4.5	3.8
109	6 21	13 65	.008	.054	.033	1.7	4.4	3 4
Maximum Size of Aggregate—No. 4 Mesh								
110	11 62	7 80	.010	.048	.032	0.9	7.9	7.5
111	11.35	9.18	.013	.051	.033	1.1	8.1	7 6
112	11.02	10.33	.010	.052	.034	1.2	8.0	7.5
113	10.75	11.18	.013	.053	034	1.3	7.9	7.3
114	10 38	12.04	008	.054	.035	1.4	7.7	7.1
115	9.97	13.13	020	.057	.036	1.5	7.6	7.0
116	9.00	15.85	.011	.060	.037	1 8	7.3	6.5

were necessary to insure adequate resistance to freezing and thawing.

A comparison of the optimum concrete air contents determined from Figure 9 and the concrete air contents obtained with the Type IA cement is shown in Table 10-A.

The data in Table 10-A indicate a persistent tendency, throughout the range of variations in cement content and variations in mortar content as a result of the use of different maximum sizes of aggregate, for the Type IA cement to provide approximately the amount of air indicated to be desirable. In some cases the air contents provided by the Type IA

TABLE 12
LENGTH AND WEIGHT CHANGES OF CONCRETES PRIOR TO FREEZING AND THAWING
5 and one-half sacks per cu. yd. 2- to 3-in. Slump; 3- by 3- by 11¼-in. Prisms

Ref. No.	Net W/C, gal. per sk.	Air Content, Percent (Pressure)	Length Changes During Period Indicated—Percent			Weight Changes During Periods Indicated—Percent		
			14 d. Moist (+)	14 d. Air (−)	3 d. in Water (+)	14 d. Moist (+)	14 d. Air (−)	3 d. in Water (+)
			Maximum Size of Aggregate—2½ in.					
31	5.04	1.14	.005	.035	.023	0.7	1.9	1.6
32	4.99	1.52	.004	.035	.023	0.6	1.8	1.4
33	4.88	2.07	.005	.034	.022	0.6	1.7	1.3
34	4.84	2.55	.004	.038	.024	0.6	1.7	1.4
35	4.85	3.20	.005	.034	.022	0.6	1.7	1.4
36	4.82	3.89	.004	.035	.023	0.6	1.7	1.4
37	4.69	5.11	.004	.034	.021	0.6	1.7	1.5
38	4.64	7.98	.005	.038	.024	0.7	1.9	1.5
			Maximum Size of Aggregate—1½ in.					
1	5.13	1.43	.006	.032	.020	0.6	1.8	1.5
2	5.01	2.51	.005	.034	.022	0.5	1.7	1.4
3	4.89	2.86	.005	.036	.022	0.5	1.8	1.4
4	4.85	3.55	.004	.034	.022	0.4	1.6	1.4
5	4.78	3.99	.005	.035	.023	0.5	1.7	1.4
6	4.67	5.72	.005	.037	.023	0.5	1.8	1.4
7	4.58	8.76	.006	.041	.025	0.6	1.9	1.5
			Maximum Size of Aggregate—¾ in.					
8	5.54	1.98*	.005	.039	.025	0.7	2.1	1.6
9	5.51	2.66	.004	.039	.025	0.6	2.2	1.7
10	5.44	3.68	.005	.041	.026	0.6	2.4	1.8
11	5.35	4.21	.004	.040	.026	0.6	2.2	1.7
12	5.25	4.69	.005	.041	.026	0.6	2.2	1.7
13	5.23	5.63	.006	.041	.026	0.7	2.2	1.7
14	5.04	7.53	.005	.043	.027	0.6	2.1	1.6
15	4.78	10.49	.006	.048	.029	0.7	2.3	1.6
			Maximum Size of Aggregate—⅜ in.					
16	6.51	4.05	.005	.048	.031	0.7	3.1	2.4
17	6.36	4.99	.005	.049	.030	0.7	3.1	2.4
18	6.04	6.06	.005	.047	.030	0.7	3.0	2.2
19	5.96	6.66	.004	.049	.031	0.7	2.9	2.2
20	5.85	7.64	.004	.049	.031	0.7	2.9	2.1
21	5.67	8.30	.005	.052	.032	0.7	2.7	2.1
22	5.35	9.89	.004	.053	.033	0.7	2.6	1.9
23	5.01	12.88	.005	.058	.035	0.7	2.5	1.8
			Maximum Size of Aggregate—No. 4 Mesh					
24	7.88	7.25	.010	.057	.035	0.9	4.9	4.2
25	7.69	8.49	.009	.056	.034	1.0	4.8	3.9
26	7.47	9.84	.010	.058	.035	1.0	4.8	3.9
27	7.26	10.62	.010	.059	.035	1.1	4.9	3.9
28	6.99	11.65	.011	.060	.034	1.0	4.6	3.[illegible]
29	6.76	12.33	.009	.061	.036	1.2	4.7	3.6
30	6.45	14.33	.010	.066	.037	1.2	4.7	3.4

cement were below those considered to be optimum. In those cases, the frost resistances were acceptable but not as high as at the optimum air content.

It is of interest also that for the 4-sk.-per-cu.-yd. mixes made with ⅜-in. and No. 4 maximum size aggregate, which were the exceptions to the data indicating that a constant amount of air in the mortar fraction would provide adequate durability, the Type IA cement provided slightly more air than the optimum air contents determined from Figure 9.

Characteristics of Air Voids in Hardened Concrete—Table 18 shows the bubble-spacing factors of the air voids in the concretes having

TABLE 13
LENGTH AND WEIGHT CHANGES OF CONCRETES PRIOR TO FREEZING AND THAWING
7 sacks per cu. yd. 2- to 3-in. Slump. 3- by 3- by 11 and one-quarter-in. Prisms

Ref. No.	Net W/C, gal. per sk.	Air Content, Percent (Pressure)	Length Changes During Period Indicated—Percent			Weight Changes During Period Indicated—Percent		
			14 d. Moist (+)	14 d. Air (−)	3 d. in Water (+)	14 d. Moist (+)	14 d. Air (−)	3 d. in Water (+)
			Maximum Size of Aggregate—2½ in.					
39	4.16	1.12	.004	.029	.021	0.8	1.5	1.2
40	4.14	1.40	.003	.028	.021	0.8	1.4	1.1
41	4.12	1.73	.003	.028	.021	0.8	1.4	1.1
42	4.10	2.04	.003	.029	.022	0.8	1.4	1.1
43	4.11	2.59	.002	.028	.021	0.8	1.5	1.1
44	4.10	2.77	.003	.030	.022	0.7	1.4	1.1
45	4.04	3.65	.003	.033	.023	0.8	1.5	1.2
46	4.00	6.05	.004	.036	.026	0.9	1.6	1.2
			Maximum Size of Aggregate—1½ in.					
47	4.28	1.31	.005	.027	.020	0.8	1.4	1.1
48	4.26	1.60	.004	.029	.020	0.6	1.2	1.1
49	4.22	1.99	.005	.028	.020	0.7	1.3	1.0
50	4.21	2.28	.005	.027	.020	0.7	1.4	1.1
51	4.16	2.60	.005	.029	.021	0.7	1.3	1.1
52	4.13	2.87	.005	.031	.022	0.6	1.3	1.1
53	4.10	3.77	.005	.031	.022	0.7	1.3	1.1
54	4.02	5.51	.005	.031	.022	0.7	1.4	1.2
			Maximum Size of Aggregate—¾ in.					
55	4.58	2.10	.008	.037	.021	0.8	1.7	1.2
56	4.51	2.46	.007	.033	.021	0.7	1.7	1.2
57	4.46	2.89	.007	.035	.022	0.7	1.6	1.1
58	4.44	3.26	.006	.037	.024	0.7	1.7	1.2
59	4.42	3.76	.006	.037	.022	0.7	1.7	1.2
60	4.41	4.34	.006	.038	.023	0.7	1.7	1.2
61	4.31	5.20	.006	.039	.025	0.7	1.7	1.2
62	4.27	8.08	.007	.042	.024	0.7	1.8	1.2
			Maximum Size of Aggregate—⅜ in.					
63	5.10	3.94	.007	.044	.029	0.9	2.4	1.6
64	5.04	4.82	.007	.044	.030	0.8	2.4	1.7
65	4.99	5.40	.007	.045	.030	0.8	2.4	1.7
66	4.89	5.81	.005	.043	.029	0.8	2.4	1.6
67	4.80	6.39	.009	.047	.031	0.8	2.3	1.6
68	4.71	6.88	.008	.047	.031	0.8	2.3	1.6
69	4.63	8.07	.009	.048	.031	0.8	2.4	1.6
70	4.49	10.74	.008	.052	.034	1.0	2.4	1.6
			Maximum Size of Aggregate—No. 4 Mesh					
71	6.04	7.90	.012	.054	.033	1.0	3.6	2.6
72	5.96	8.77	.007	.052	.033	1.0	3.7	2.5
73	5.90	9.66	.007	.053	.035	1.1	3.7	2.6
74	5.81	10.10	.009	.054	.034	1.2	3.7	2.5
75	5.70	10.76	.013	.055	.034	1.1	3.5	2.4
76	5.61	11.42	.008	.058	.036	1.2	3.6	2.4
77	5.40	12.56	.007	.057	.035	1.3	1.6	2.3

optimum air contents shown in Table 17. The bubble-spacing factor is a measure of the average maximum distance from a point in the cement paste to the nearest air void, this being an indication of the distance water would have to travel, during the freezing process, to reach a protective air void. If this distance is relatively large, water moving through the paste during freezing may develop pressures sufficient to cause failure before the water can reach an air void. A relatively small distance would tend to reduce these pressures. The spacing factors shown range from 0.006 to 0.013 in., averaging 0.009 in. In general, the

TABLE 14

RESULTS OF SURFACE SCALING AND FREEZING AND THAWING TESTS—4 SACKS PER CU. YD.

See text for description of test specimens and procedure. Three specimens per reference number.
Cement content of concretes—4 sacks per cu. yd. Slump—2 to 3 inches.
Elgin, Illinois, sand and Eau Claire, Wis., gravel.
Curing: 14 days moist, 14 days in air and 3 days in water prior to start of tests.

Ref. No.	Air Content, Percent Pressure	Rating of Slab Surface After 125 Cycles of F. and T.	Expansion, Change in Dynamic E and Weight Loss During 300 Cycles F. and T.			Number of Cycles of F. and T. for 0.10 Percent Expansion
			Percent Exp.	Percent Change in E	Percent Wt. Loss	
			Maximum Size of Aggregate—2½ in.			
78	2.13	(95)[a]	(175)[a]	(175)	(175)	161
79	2.91	2	0 047	−58	9.2	386
80	3.80	2−	0.023	−4	1.6	0.030% at 400 cycles
81	4.36	2−	0.020	+3	0.5	0.024% at 400 cycles
82	5.04	1+	0.019	+3	0.2	0.022% at 400 cycles
83	5.77	1+	0 018	+4	0.1	0.021% at 400 cycles
84	7.28	1−	0.016	+3	0.1	0.019% at 400 cycles
85	10 62	1−	0.022	−10	0 3	0.026% at 400 cycles
			Maximum Size of Aggregate—1½ in.			
86	2.63	(109)	(175)	(175)	(175)	152
87	3.44	2	0 063	−55	9.0	353
88	4.28	2	0 018	+1	1 3	0.025% at 400 cycles
89	4 57	1+	0 017	+4	0.6	0.024% at 400 cycles
90	5 54	1+	0.018	+4	0.2	0.022% at 400 cycles
91	5.79	1+	0.015	+4	0.1	0 020% at 400 cycles
92	6.94	1−	0.015	+5	0	0.019% at 400 cycles
93	10.23	0+	0 020	−3	0.1	0 025% at 400 cycles
			Maximum Size of Aggregate—¾ in.			
94	3.11	(76)	(100)	(100)	(100)	90
95	4.21	3	0.115	−75	22.3	290
96	5 25	2	0.026	−18	7.1	0.034% at 375 cycles
97	5.96	2−	0 015	−2	3.1	0.018% at 375 cycles
98	6.65	2−	0.016	+1	2.4	0.019% at 375 cycles
99	7.35	1+	0 016	+3	1.0	0 018% at 375 cycles
100	9.86	1	0 017	+4	0.5	0.019% at 375 cycles
101	12.24	1−	0.018	+1	0.3	0.021% at 375 cycles
			Maximum Size of Aggregate—⅜ in.			
102	5.38	(66)	(75)	(75)	(75)	42
103	6.58	5−	(150)	(150)	(150)	136
104	7.47	2+	0.043	−44	18.1	0.054% at 325 cycles
105	8.28	2+	0.024	−18	9.0	0.027% at 325 cycles
106	9.25	2	0.018	−7	4.8	0.020% at 325 cycles
107	9.61	2−	0.018	−3	3.3	0 019% at 325 cycles
108	11.43	1+	0.019	−1	1.6	0 019% at 325 cycles
109	13.65	0+	0.020	−2	1.4	0.020% at 325 cycles
			Maximum Size of Aggregate—No. 4 Mesh			
110	7.80	(39)	(25)	(25)	(25)	19
111	9.18	(61)	(50)	(50)	(50)	39
112	10.33	(107)	(190)	(190)	(190)	173
113	11.18	(113)	0 071	−59	33.4	0.087% at 325 cycles
114	12.04	3+	0 027	−38	22.5	0.031% at 325 cycles
115	13.13	2+	0 021	−29	18.0	0.023% at 325 cycles
116	15.85	2	0.017	−15	9 1	0 018% at 325 cycles

[a] Numbers in parentheses indicate cycles at which test was discontinued due to excessive scaling or expansion.

spacing factors decrease with increase in cement content. Little other experimental evidence is available as to the effect of bubble-spacing factor on the resistance of concrete to freezing and thawing. It appears that for these optimum air contents, the spacing factors are approximately equal. This may be of significance and should be considered for further

TABLE 15

RESULTS OF SURFACE SCALING AND FREEZING AND THAWING TESTS—5½ SACKS PER CU. YD.

See text for description of test specimens and procedure. Three specimens per reference number.
Cement content of concretes—5½ sacks per cu. yd. Slump—2 to 3 in.
Elgin, Illinois, sand and Eau Claire, Wisconsin, gravel.
Curing: 14 days moist, 14 days in air and 3 days in water prior to start of tests.

Ref. No.	Air Content, Percent Pressure	Rating of Slab Surface After 125 Cycles of F. and T.	Expansion, Change in Dynamic E and Weight Loss During 300 Cycles F. and T.			Number of Cycles of F. and T. for 0.10 Percent Expansion
			Percent Exp.	Percent Change in E	Percent Wt. Loss	
			Maximum Size of Aggregate—2½ in.			
31	1.14	(100)[a]	(100)[a]	(100)	(100)	63
32	1 52	2+	(225)	(225)	(225)	146
33	2.07	2−	0.101	−68	1.6	300
34	2.55	1+	0.048	−19	0.5	486
35	3.20	1+	0.038	−5	0.2	620
36	3.89	1	0.035	−5	+0.2	697
37	5.11	1	0.024	−3	+0.3	b
38	7.98	1	0 026	−2	+0.3	b
			Maximum Size of Aggregate—1½ in.			
1	1.43	4−	(100)	(100)	(100)	67
2	2.51	2	0.089	−54	1.2	325
3	2.86	2	0.045	−6	0.4	523
4	3.55	2−	0.039	−3	+0.1	628
5	3.99	2−	0 032	0	0.1	767
6	5.72	1	0.025	+4	+0.1	0.093% at 1200 cycles
7	8.76	1	0.024	+3	0.2	b
			Maximum Size of Aggregate—¾ in.			
8	1.98	4	(125)	(125)	(125)	92
9	2.66	3	0.142	−62	6.6	255
10	3.68	3−	0.039	−9	1.7	575
11	4.21	3−	0.028	+1	0.8	850
12	4.69	2	0.024	+2	0.2	1050
13	5.63	2	0.022	+3	0	1150
14	7.53	2	0.020	+5	+0.2	0.080% at 1200 cycles
15	10.49	2	0.022	+6	0.1	b
			Maximum Size of Aggregate—⅜ in.			
16	4.05	3	0.190	−81	35.2	232
17	4.99	2	0.035	−23	9.8	669
18	6.06	2	0.023	0	1.3	1200
19	6.66	2−	0 021	+3	0.3	0.083% at 1200 cycles
20	7.64	2−	0.019	+4	+0.2	0.069% at 1200 cycles
21	8 30	1+	0.021	+5	+0.1	0.073% at 1200 cycles
22	9.89	1	0.017	+5	+0.4	0.054% at 1200 cycles
23	12.88	1−	0.021	+4	+0.5	b
			Maximum Size of Aggregate—No. 4 Mesh			
24	7.25	4+	0.133	−65	36.9	265
25	8.49	2	0.028	−19	11.5	845
26	9.84	2	0.022	−1	3.5	0.095% at 1200 cycles
27	10.62	2−	0.021	−1	2.4	0.081% at 1200 cycles
28	11.65	2−	0.021	+1	2.1	0.080% at 1200 cycles
29	12.33	1+	0.020	+3	1.1	b
30	14.33	1	0.020	+4	1.3	b

[a] Numbers in parentheses indicate cycles at which test was discontinued due to excessive scaling or expansion.
[b] Tests discontinued due to lack of freezer space.

study. For all of the concretes included in these tests, both non-air-entrained and air-entrained, the bubble-spacing factors ranged from a low of 0.003 in. to a high of 0.038 in.

Entrained Air on Resistance to Salt Scaling—Tables 14, 15, and 16 show the results of tests for resistance to surface scaling resulting from the use of calcium chloride for ice removal.

TABLE 16

RESULTS OF SURFACE SCALING AND FREEZING AND THAWING TESTS—7 SACKS PER CU. YD.

See text for description of test specimens and test procedures. Three specimens per reference number.
Cement content of concretes—7 sacks per cu. yd. Slump—2 to 3 in.
Elgin, Illinois, sand and Eau Claire, Wisconsin, gravel.
Curing: 14 days moist, 14 days in air and 3 days in water prior to start of tests.

Ref. No.	Air Content, Percent Pressure	Rating of Slab Surface After 125 Cycles of F. and T.	Expansion, Change in Dynamic E and Weight Loss During 300 Cycles F. and T.			Number of Cycles of F. and T. for 0.10 Percent Expansion
			Percent Exp.	Percent Change in E	Percent Wt. Loss	
			Maximum Size of Aggregate—2½ in.			
39	1.12	2	(125)[a]	(125)	(125)	46
40	1.40	1−	(250)	(250)	(250)	129
41	1.73	0+	(275)	(275)	(275)	232
42	2.04	0+	.099	−44	1.1	305
43	2.59	0+	.074	−18	0 7	260
44	2.77	0+	.058	−14	0.6	409
45	3.65	0+	.038	−4	0 7	650
46	6.05	0+	.026	0	0.7	0.056% at 650 cycles
			Maximum Size of Aggregate—1½ in.			
47	1.31	(102)[a]	(150)	(150)	(150)	55
48	1.60	0+	(250)	(250)	(250)	132
49	1.99	0+	(283)	(283)	(283)	263
50	2.28	0+	.093	−27	0.6	310
51	2.60	0+	.072	−27	0.6	364
52	2.87	0+	.062	−18	0.5	404
53	3.77	0+	.038	−5	0.6	600
54	5.51	0+	.028	−2	0.5	0.062% at 600 cycles
			Maximum Size of Aggregate—¾ in.			
55	2.10	4	(100)	(100)	(100)	40
56	2.46	1+	(225)	(225)	(225)	88
57	2.89	1−	(292)	(292)	(292)	176
58	3.26	1−	.134	−47	3.3	257
59	3.76	1−	.134	−41	1.9	257
60	4.34	0+	.076	−21	1 3	352
61	5.20	0+	.032	−2	1.0	0.077% at 600 cycles
62	8.08	0+	.026	−1	0.9	0.047% at 600 cycles
			Maximum Size of Aggregate—⅜ in.			
63	3.94	2−	(225)	(225)	(225)	101
64	4.82	1−	(275)	(275)	(275)	258
65	5.40	1−	.059	−11	1.7	435
66	5.81	1−	.046	−5	0.7	0.097% at 550 cycles
67	6.39	1−	.037	−3	0.7	0.076% at 550 ccyles
68	6.88	0+	.030	−2	0.7	0.062% at 550 cycles
69	8.07	0+	.027	−1	0 3	0.047% at 550 cycles
70	10.74	0+	.021	+1	0.2	0.036% at 550 cycles
			Maximum Size of Aggregate—No. 4 Mesh			
71	7.90	2−	.063	−24	10.2	416
72	8.77	1+	.041	−10	4.4	0.063% at 475 cycles
73	9.66	1−	.035	−4	2.2	0.053% at 475 cycles
74	10.10	1−	.033	−2	1.2	0.050% at 475 cycles
75	10.76	1−	028	−2	1.3	0.043% at 475 cycles
76	11.42	1−	.028	0	0.9	0.041% at 475 cycles
77	12.56	1−	.029	+1	0.5	0.035% at 475 cycles

[a] Numbers in parentheses indicate cycles at which test was discontinued due to excessive scaling or expansion.

The ratings shown were determined by visual examination of the surface after 125 cycles of the test procedure.

In all cases a considerable improvement in resistance to surface scaling was apparent with the first increment of intentionally entained air. There appears to be no clearly defined optimum air content as developed in the

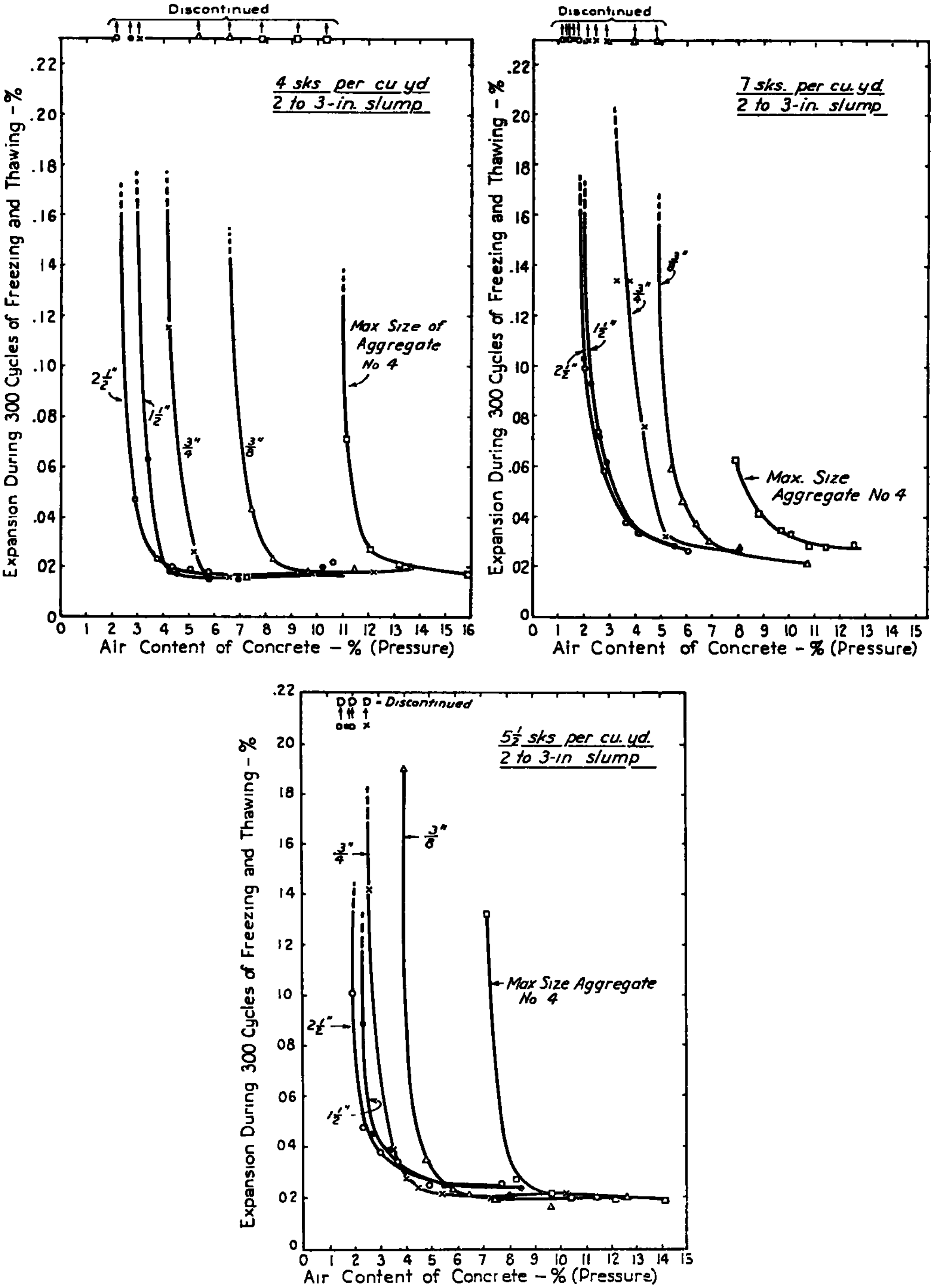

Figure 9. Expansion of concretes during 300 cycles of freezing and thawing.

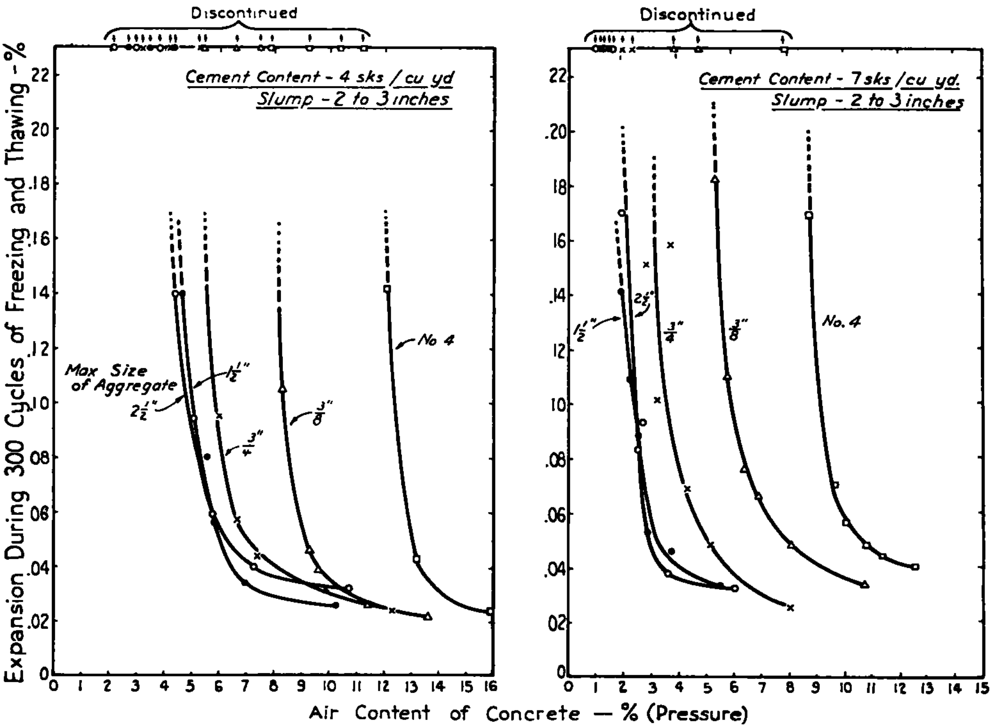

Figure 10. Expansion of concretes during 300 cycles of freezing and thawing.

TABLE 17

CHARACTERISTICS OF CONCRETES AT OPTIMUM AIR CONTENTS

Optimum concrete air contents determined visually from Figure 9

Air contents of mortar fractions calculated[a] and shown in Figure 11.

Air contents of paste fractions calculated [a] Net W/C data from Figure 3.

Maximum Size of Aggregate	Optimum Concrete Air—percent	Data for Optimum Concretes		
		Percent Air in Mortar Fraction	Percent Air in Paste Fraction	Net W/C, gal./sk.
Cement Content—4 Sacks per Cu. Yd.				
2½ in.	4.5	8 8	18.5	6.30
1½ in.	4.5	8.3	18.2	6.60
¾ in.	5.5	8.9	19.8	7.55
⅜ in.	8.5	11.1	26 2	8.50
No. 4	12.5	12.5	31 6	10.30
Cement Content—5½ Sacks per Cu. Yd.				
2½ in.	4.5	9.1	16.7	4 75
1½ in.	4.5	8.5	16 4	4 75
¾ in.	5.0	8.3	16 9	5.25
⅜ in.	6.5	8.7	19 7	6.00
No. 4	9.0	9.0	23 0	7.55
Cement Content—7 Sacks per Cu. Yd.				
2½ in.	4.5	9.2	14 7	4.05
1½ in.	4.5	8.4	14.3	4.05
¾ in.	5.5	9.2	16.8	4.30
⅜ in.	7.0	9.6	19.4	4.75
No. 4	10 0	10.0	23.4	5.80

[a] (See footnote in next column.)

TABLE 18

BUBBLE-SPACING FACTOR FOR CONCRETES OF OPTIMUM AIR CONTENT

Bubble spacing factor determined by the linear traverse method and calculated by the method outlined in Bulletin 33, Research Laboratories, Portland Cement Association.

Maximum Size of Aggregate	Cement Content—sacks per cu. yd.		
	4.0	5.5	7.0
	Bubble Spacing Factor—In.		
2½ in.	0 012	0.007	0.007
1½ in.	0.013	0.008	0 008
¾ in.	0.013	0.009	0.007
⅜ in.	0.009	0.011	0.008
No. 4	0.006	0.012	0.008

freezing-and-thawing tests. For the 4- and 5½-sack concretes, optimum resistance to surface scaling was achieved at those air contents obtained with Type IA cement. Further increases in air content resulted in only slight

[a] Percent air in mortar fraction $= \frac{A}{C+W+S+A} \times 100.$

Percent air in paste fraction $= \frac{A}{C+W+A} \times 100.$

where C = absolute volume of cement
W = volume of net mixing water
S = absolute volume of sand (minus No. 4 mesh), saturated-surface-dry.
A = volume of air voids.

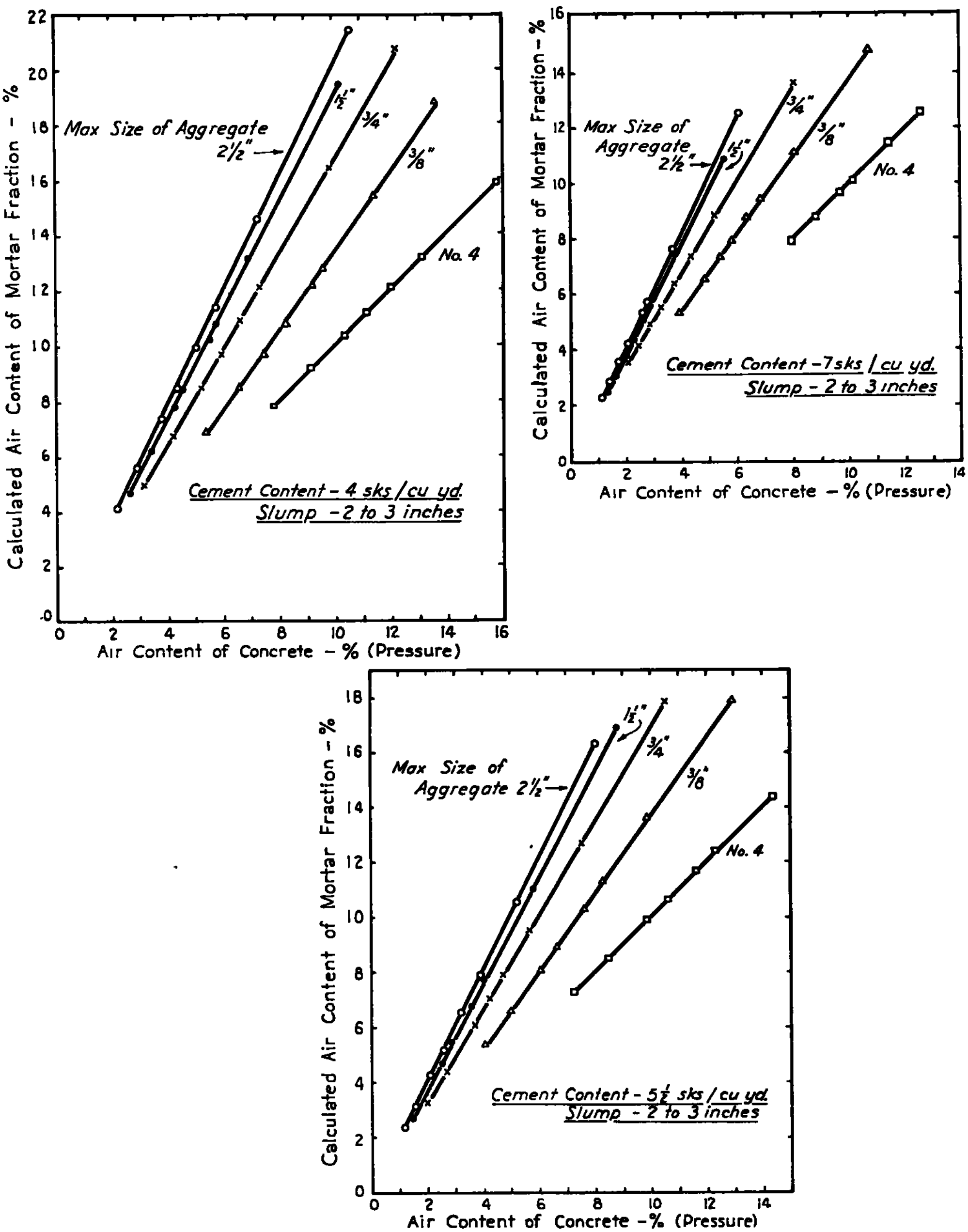

Figure 11. Relationships between air content of concrete and calculated air-content of mortar fraction.

further increases in resistance. For the 7-sack concretes, air contents intermediate to those obtained with the Type I and Type IA cements resulted in excellent resistance to surface scaling, indicating the beneficial effect of the higher cement content.

GENERAL OBSERVATIONS

These laboratory tests confirm the considerable amount of laboratory and field data indicating the greatly increased resistance to freezing and thawing and to surface scaling achieved by the use of entrained air and provide information enabling a more suitable approach to the problem of specifying the amount of air required for adequate resistance to frost action.

During this study, corollary tests and observations were made to secure information which would assist in the determination of basic factors controlling resistance of concrete to freezing and thawing. A study of data from these corollary tests indicates the presence of variables which are difficult to evaluate. These studies are continuing, with particular emphasis on determinations of freezable water present at time of freezing, possible effect of thermal incompatibility of concrete constituents, and the effect of changes in curing conditions.

SUMMARY

The following points summarize the information developed in these tests, many confirming the results of previous tests and tests by other investigators:

1. For constant cement content and consistency, the reduction in strength with entrainment of air decreases as the maximum size of aggregate decreases, due to the greater reductions in water requirements possible with the smaller size aggregates.

2. For a particular consistency, the reduction in strength with entrainment of air decreases with a decrease in cement content, due to the greater reductions in water requirements possible in the leaner mixes.

3. There was no significant effect of air content on volume change during moist storage or air storage, on weight change during moist storage or air storage, or on absorption during 3-day immersion in water.

4. In all cases, the entrainment of air increased the resistance of concrete to freezing and thawing and to surface scaling resulting from the use of salts for ice removal.

5. The optimum air content for these concretes, insofar as resistance to freezing and thawing is concerned, increased as the maximum size of aggregate decreased. (The optimum air content is defined as that air content beyond which further increases in air result in no further appreciable increase in resistance). In general, the use of Type 1A cement afforded a self-regulating means for providing about the air content shown to be optimum.

6. For concretes whose curing included a period of air-drying, at the particular consistency used and for any one maximum size of aggregate, there was no significant effect of cement content on the optimum air contents.

7. For concretes whose curing included a period of air-drying, these tests indicate that for a particular consistency, concrete resistant to freezing and thawing can be secured by providing a relatively constant air content in the mortar fraction, regardless of cement content or mortar content of the mix. For these tests, with only two exceptions, this calculated mortar air content was 9 ±1 percent. When specifying air contents for concretes, due consideration must be given to the maximum size of aggregate used.

8. For concretes whose curing included a period of air-drying, the calculated spacing factor for the air voids at the optimum air contents ranged from 0.006 to 0.013 in., averaging 0.009 in.

9. Concretes cured continuously moist required slightly more entrained air for adequate resistance to freezing and thawing than concretes whose curing included a period of air-drying, except for the 7-sack concretes made with maximum sizes of aggregate $\frac{3}{4}$ in. and larger