Effect of Entrained Air on Strength and Durability of Concrete with Various Sizes of Aggregates

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Previous tests using a natural sand and a curshed siliceous gravel indicated that, for concretes of constant cement content and consistency (varying water-cement ratio), adequate resistance to freezing and thawing of air-dried concretes was secured when the air content of the mortar fraction was 9 ± 1 percent, regardless of the maximum size of aggregate used.

The tests reported herein are for concretes made with cements from the same source as the initial tests and the same natural sand. However, the coarse aggregate used was a crushed limestone with particle shape and texture different from those of the gravel previously used. Three cement contents were used at a constant slump of 5 to 6 inches: 4.0, 5.5 and 7.0 sacks per cubic yard of concrete. The maximum sizes of aggregate used were $^3/_8$-in., $^3/_4$-in. and $1^1/_2$-in. For each combination of cement content and maximum size of aggregate, five concretes covering a fairly wide range of air contents were prepared.

The results of freezing and thawing tests of these concretes confirmed the results of the earlier tests. Adequate resistance to freezing and thawing was obtained when the air content of the mortar fraction was in the range of 9 ± 1 percent.

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

●THIS is a second report concerning a group of tests designed to provide quantitative information regarding the proper amount of entrained air for adequate frost resistance and the effect of the entrained air on the strength of concretes made with various maximum sizes of aggregate.

The first series of tests[1] using a natural sand and a crushed gravel indicated that, for concretes of constant cement content and consistency, adequate resistance to freezing and thawing of air-dried concretes was secured when the air content of the mortar fraction was in the range of 9 ± 1 percent regardless of the maximum size of aggregate used. In these tests, the Type IA cement generally provided this necessary amount of air as required.

The second series of tests, the results of which are reported herein, were made using a different type of coarse aggregate and concrete of higher slump to determine whether, with these changes, the same requirement would be found for air content of mortar.

SCOPE OF TESTS

The concretes used in this second series of tests had cement contents of 4.0, 5.5 and 7.0 sk. per cu. yd. with net water-cement ratios varied so that the consistency was maintained at 5 to 6 inches as measured by the slump test. For each cement content, three maximum sizes of aggregate were used: $^3/_8$-in., $^3/_4$-in. and $1^1/_2$-in. Five concretes were prepared for a particular cement content and maximum size of aggregate covering a fairly wide range of air contents. The range in air contents was ob-

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[1] "Effect of Entrained Air on Strength and Durability of Concrete Made With Various Maximum Sizes of Aggregate," by Paul Klieger, Proceedings Thirty-First Annual Meeting, 1952 Highway Research Board. Reprinted as Bulletin 40, Portland Cement Association, Chicago, Ill.

TABLE 1

CHEMICAL COMPOSITION OF CEMENTS

Chemical analyses of cements made in accordance with ASTM Methods of Test current in February, 1953. Sodium oxide and potassium oxide by flame photometry, ASTM C228-49T.

Cement	Major Components - %						Minor Components - %						
											Alkalies		
Lot No.	SiO_2	Al_2O_3	Fe_2O_3	Total CaO	MgO	SO_3	Ign. Loss	Mn_2O_3	Free CaO	Insol. Res.	Na_2O	K_2O	Total as Na_2O
TYPE I CEMENTS													
18787	22.03	5.98	2.40	62.35	2.45	2.30	1.06	0.07	1.09	0.18	0.13	1.12	0.87
18788	20.77	6.28	3.12	63.67	1.90	1.79	1.30	0.20	1.11	0.11	0.27	0.55	0.63
18789	20.73	6.10	2.78	63.16	2.43	2.11	1.64	0.47	1.72	0.16	0.11	0.15	0.21
18790[a]	21.18	6.12	2.77	63.06	2.26	2.07	1.33	0.25	1.31	0.15	0.17	0.16	0.57
TYPE IA CEMENTS													
18791	21.98	5.76	2.38	62.66	2.39	2.39	1.00	0.07	0.79	0.10	0.14	1.07	0.84
18792	20.59	6.55	3.17	63.90	2.04	1.82	0.68	0.23	0.64	0.11	0.27	0.55	0.63
18793	21.31	5.27	2.48	64.01	2.80	1.90	1.51	0.49	1.73	0.16	0.08	0.14	0.17
18794[a]	21.29	5.86	2.68	63.52	2.41	2.04	1.06	0.26	1.05	0.12	0.16	0.59	0.55

[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.

tained by using Type I cement, Type I and Type IA blend, Type IA and Type IA plus the addition of neutralized Vinsol resin in solution during mixing.

The concretes prepared were subjected to the following tests: (1) flexural and compressive strength tests of 6 by 6 by 30-in. beams at 28 days, (2) freezing and thawing tests of 3 by 3 by 11¼-in. prisms, both air dried and continuously moist cured, (3) resistance to surface scaling resulting from the use of salts for ice removal purposes and (4) drying shrinkage and absorption tests.

In addition, the characteristics of the air voids in the hardened concrete are being determined, together with actual determinations of freezable water and length change during freezing. These data will form the basis for a future report evaluating their influence on the measured durabilities.

MATERIALS

The cements were a Type I blend and a Type IA blend, each prepared from three

TABLE 2

POTENTIAL COMPOUND COMPOSITION OF CEMENTS

Corrected for free CaO

Cement	Calculated Compound Composition - %					
Lot No.	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	Free CaO
TYPE I CEMENTS						
18787	31.7	39.2	11.8	7.3	3.91	1.09
18788	45.0	25.6	11.4	9.5	3.04	1.11
18789	41.5	28.1	11.5	8.5	3.59	1.72
18790[a]	39.4	31.0	11.6	8.4	3.51	1.31
TYPE IA CEMENTS						
18791	35.9	36.0	11.2	7.2	4.06	0.79
18792	47.3	23.4	12.0	9.6	3.10	0.64
18793	47.2	25.5	9.8	7.5	3.23	1.73
18794	43.5	28.3	11.0	8.1	3.46	1.05

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

TABLE 3

MISCELLANEOUS PHYSICAL TESTS OF CEMENTS

Tests made in accordance with ASTM Methods of Test current in November, 1952. Each value is the average of two or more determinations.

Cement Lot No.	Fineness		Specific Gravity	Normal Consistency, %	Time of Setting				Autoclave Exp., %	Air Content, % 1-4 Mortar
	Sp.Surf. sq. cm. per g. Wagner	Passing 325 Mesh %			Vicat Initial h. m.	Vicat Final h. m.	Gillmore Initial h. m.	Gillmore Final h. m.		
TYPE I CEMENTS										
18787	1710	94.8	3.148	26.5	2:30	5:45	3:30	5:55	0.21	8.9
18788	1710	92.5	3.141	24.5	2:40	5:40	3:30	5:45	0.21	14.5
18789	1800	91.8	3.124	26.0	3:15	6:30	4:10	6:30	0.09	8.9
18790	1740[a]	93.0[a]	3.138[a]	25.0	3:00	6:05	3:55	6:15	0.22	9.5
TYPE IA CEMENTS										
18791	1750	96.3	3.153	26.5	3:55	6:40	4:40	6:40	0.19	16.7
18792	1760	94.1	3.170	25.0	3:00	6:05	4:10	6:10	0.20	18.1
18793	1860	93.7	3.127	27.5	3:50	6:30	4:35	6:40	0.10	20.4
18794	1790[a]	94.7[a]	3.150[a]	26.0	4:00	7:00	4:55	7:10	0.14	18.3

[a] Arithmetical average of three individual cements.

different cements 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 and 3. Tensile and compressive strengths of mortars are shown in Table 4.

Both aggregates used in these tests have excellent service records. Grading, specific gravity and absorption data are shown in Table 5. The fine aggregate used was sand from Elgin, Illinois, a predominatly dolomitic natural sand. The coarse aggregate was a crushed limestone from Thornton, Illinois.

Aggregates were air dried and screened into various size fractions prior to use, six sizes for the fine aggregate and three sizes for the coarse aggregate as shown in Table 5. Aggregates were weighed air dry and soaked for 18-20 hours prior to mixing of concrete batches.

TABLE 4

STRENGTH TESTS OF MORTARS

Briquets: ASTM C190-49. Cubes: ASTM C109-50.
Each value is the average of three specimens, each made on a different day.

Cement Lot No.	Tensile Strength, 1-3 Std. Sand Mortar Briquets - lb. per sq. in.				Compressive Strength, 2-in. Plastic Mortar Cubes, lb. per sq. in.			
	1d.	3d.	7d.	28d.	1d.	3d.	7d.	28d.
TYPE I CEMENTS								
18787	220	380	460	490	730	1790	2710	4610
18788	185	375	435	465	545	1720	2910	4520
18789	175	340	390	535	510	1450	2280	4370
18790	175	360	385	525	540	1690	2650	4800
TYPE IA CEMENTS								
18791	195	360	400	455	730	1830	2720	4540
18792	160	370	410	470	540	1910	3220	4920
18793	135	280	335	440	480	1290	2250	4090
18794	165	345	400	455	580	1700	2780	4570

TABLE 5

DATA ON AGGREGATES

Elgin, Illinois, Sand

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

Thornton, Illinois, Crushed Limestone

Maximum Size of Aggregate, in.	Grading - % Retained on Sieve Size Indicated				Bulk Specific Gravity, S.S.D.[a]	24-Hour Absorption, % by Wt.
	1½-in.	¾-in.	⅜-in.	No. 4		
1½	0	50	75	100	2.631	1.49
¾	0	0	50	100	2.632	1.73
⅜	0	0	0	100	2.637	1.90

[a] Saturated, surface-dry.

TABLE 6

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

Concrete specimens: 6 by 6 by 30-in. beams. Elgin, Illinois, sand and Thornton, Illinois, stone.
Cement content of all concretes - 4 sk. per cu. yd. Slump: 5 to 6 inches.
Type I cement - Lot 18790. Type IA cement - Lot 18794.
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 of Cement Used		Net W/C, gal. per sk.	Slump, in.	% Sand, Abs. Vol.	Mortar Content % by Abs. Vol.	Air Content, % (pressure)	28d. Str.-lb. per sq. in.	
	I	IA						Mod. of Rupture 3rd Pt. Loading 18-in. Span	Comp. Str. 6-in. Modified Cubes
MAXIMUM SIZE OF AGGREGATE - 1½-IN.									
301	100	0	8.35	6.2	46.0	60.0	2.37	490	3180
302	50	50	7.67	5.9	44.0	59.3	5.01	530	3310
303	0	100	7.22	5.0	42.0	58.3	6.94	525	3370
304	0	100[a]	6.84	5.1	40.0	57.4	8.45	500	3210
305	0	100[a]	6.41	5.5	38.0	57.1	11.15	445	2610
MAXIMUM SIZE OF AGGREGATE - ¾-IN.									
306	100	0	9.23	6.0	54.0	67.0	3.37	410	2300
307	50	50	8.37	5.2	51.0	65.7	6.40	475	2690
308	0	100	7.86	5.8	49.0	64.8	8.53	460	2640
309	0	100[a]	7.45	5.9	47.5	64.3	10.20	450	2740
310	0	100[a]	6.73	5.2	45.0	63.3	12.99	435	2380
MAXIMUM SIZE OF AGGREGATE - ⅜-IN.									
311	100	0	10.26	6.0	72.0	81.3	5.83	340	1640
312	50	50	9.30	5.6	69.5	80.0	8.60	360	1880
313	0	100	8.67	5.7	67.5	78.8	10.83	400	2070
314	0	100[a]	7.90	5.3	65.4	77.7	13.13	370	2110
315	0	100[a]	7.27	5.9	62.9	76.7	16.00	345	1850

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

FABRICATION OF SPECIMENS

All materials were at 73° F. at the time of mixing. Concrete batches were mixed for 3 minutes in an open-tub Lancirick mixer. Each batch contained 1.30 cu. ft. of concrete. 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 6 by 15-in. slab and four 3 by 3 by 11¼-in. prisms. A slump test and an air content determination by the pressure method were made on each batch of concrete.

Specimen molds (steel) were filled in two equal layers each rodded with a ⅝-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.

TABLE 7

CONCRETE MIX DATA AND 28-DAY MOIST-CURED STRENGTHS 5¼ SK. PER CU. YD.

Concrete specimens 6 by 6 by 30-in. beams. Elgin, Illinois, sand and Thornton, Illinois, stone.
Cement content of all concretes - 5¼ sk. per cu. yd. Slump: 5 to 6 inches.
Type I cement - Lot 18790. Type IA cement - Lot 18794.
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 of Cement Used		Net W/C, gal. per sk.	Slump, in.	% Sand, Abs. Vol.	Mortar Content % by Abs. Vol.	Air Content % (pressure)	28d. Str. - lb, per sq. in.	
	I	IA						Mod. of Rupture 3rd Pt. Loading 18-in. Span	Comp. Str. 6-in. Modified Cubes
				MAXIMUM SIZE OF AGGREGATE - 1½-IN.					
316	100	0	6.04	5.0	43.0	59.1	2.25	710	5860
317	50	50	5.75	5.0	40.5	58.2	4.29	695	5760
318	0	100	5.60	5.4	39.0	58.0	6.15	685	5440
319	0	100[a]	5.47	5.3	37.5	57.8	7.90	650	4920
320	0	100[a]	5.26	5.5	35.6	57.4	10.03	600	4090
				MAXIMUM SIZE OF AGGREGATE - ¾-IN.					
321	100	0	6.55	6.0	51.0	66.0	3.15	670	4580
322	50	50	6.10	5.3	49.0	65.3	5.60	665	4780
323	0	100	5.88	5.7	47.0	64.6	7.44	645	4540
324	0	100[a]	5.68	5.6	44.9	64.2	9.77	620	4190
325	0	100[a]	5.46	5.5	43.0	63.8	11.95	585	3850
				MAXIMUM SIZE OF AGGREGATE - ⅜-IN.					
326	100	0	7.03	5.2	68.9	79.5	5.28	570	3650
327	50	50	6.57	5.8	66.0	78.0	7.55	595	3910
328	0	100	6.34	5.7	64.4	77.3	9.30	585	3820
329	0	100[a]	5.97	5.8	62.4	76.6	11.75	570	3620
330	0	100[a]	5.73	5.7	60.4	75.9	13.70	530	3330

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

The specimens were covered with two layers of damp burlap (not in contact with the surface) and a tarpaulin over the burlap. The following day the molds were stripped. The slab specimens were then provided with a 1:2 mortar dike, approximately ¾ by ¾-in. in section, around the perimeter of the finished top surface.

CURING CONDITIONS

The beams for strength tests were cured continuously moist until time for test. Some of the prisms used in the freezing and thawing tests were cured 1 day in molds, 13 days in the moist room, 14 days in the air of the laboratory (50 percent R. H.) and 3 days in water prior to the start of tests. The remainder of the prisms were cured 1 day in molds, 27 days in the moist room and 3 days in water prior to test. Curing temperature was 73.4 ± 3° F.

The slabs for scaling test were cured 1 day in molds, 13 days in the moist room, 14 days in the air of the laboratory (50 percent R. H.) and 3 more days in air with a ⅜-in layer of water on the top surface.

TEST METHODS

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

Two complete cycles of freezing and thawing were obtained every 24 hours, the prisms being immersed in tap water at all times. The rate of cooling was approximately 20° F. per hour. Periodic determinations of changes in weight, length and sonic modulus were used as criteria of durability.

TABLE 8

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

Concrete specimens· 6 by 6 by 30-in. beams. Elgin, Illinois, sand and Thornton, Illinois, stone.
Cement content of all concretes - 7 sk. per cu. yd. Slump: 5 to 6 inches.
Type I cement - Lot 18790. Type IA cement - Lot 18794.
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 of Cement Used		Net W/C, gal. per sk.	Slump, in.	% Sand, Abs. Vol.	Mortar Content % by Abs. Vol.	Air Content, % (pressure)	28d. Str. - lb. per sq. in.	
	I	IA						Mod. of Rupture 3rd Pt. Loading 18-in. Span	Comp. Str. 6-in. Modified Cubes
				MAXIMUM SIZE OF AGGREGATE - 1½-IN.					
331	100	0	4.90	5.1	40.1	59.0	2.16	800	7260
332	50	50	4.87	5.1	38.5	58.8	3.68	760	6880
333	0	100	4.86	5.2	37.0	58.6	4.99	780	6590
334	0	100[a]	4.79	5.2	35.5	58.6	6.65	730	5940
335	0	100[a]	4.77	5.5	34.0	58.6	8.38	690	5320
				MAXIMUM SIZE OF AGGREGATE - ¾-IN.					
336	100	0	5.15	4.9	47.9	65.2	2.77	790	6480
337	50	50	5.08	5.4	46.0	64.8	4.73	790	6200
338	0	100	5.01	5.5	44.5	64.6	6.35	765	5850
339	0	100[a]	4.94	5.5	43.0	64.5	8.10	715	5290
340	0	100[a]	4.87	5.6	41.0	64.2	9.87	680	5080
				MAXIMUM SIZE OF AGGREGATE - ⅜-IN.					
341	100	0	5.55	5.9	66.9	78.9	4.57	745	5580
342	50	50	5.40	6.0	64.9	78.2	6.70	740	5470
343	0	100	5.23	5.5	63.9	77.9	7.96	715	5380
344	0	100[a]	5.08	5.7	61.9	77.1	9.78	685	5040
345	0	100[a]	4.93	5.3	60.9	76.9	11.40	650	4640

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

The surface scaling test consisted of freezing a ¼-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 freezing and thawing per day. The amount of scaling was determined by visual examination and rated numerically as follows:

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

The middle section of each 6 by 6 by 30-in. beam is being used for determining the air void characteristics of these concretes, such as bubble distribution and spacing. These determinations are being made by the linear traverse method.[2]

Companion prisms to those being subjected to the freezing and thawing test are being used for determinations of freezable water and length changes during freezing using a specially designed calorimeter strain apparatus, to be described in a future report.

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

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: 2 8 days. Curing: continously moist.
Data obtained by averaging results of tests on three like specimens.

Maximum Size of Aggregate	Average Percentage Change in Strength for Each One 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. 5 TO 6-IN. SLUMP												
1½-in.	+3.7	+3.1	+2.2	+1.5	+1.1	+0.5	+1.9	+1.9	+1.7	+1.4	+0.8	+0.2
¾-in.	+7.3	+6.1	+4.9	+3.7	+2.8	+2.0	+6.1	+6.3	+5.7	+5.0	+4.3	+3.6
⅜-in.	+3.0	+3.0	+3.1	+3.1	+2.8	+2.2	+4.9	+4.9	+5.7	+5.5	+5.0	+4.7
5½ SK. PER CU. YD. 5 to 6-IN. SLUMP												
1½-in.	-1.1	-0.9	-0.9	-1.0	-1.4	-1.6	-0.9	-0.7	-1.4	-2.0	-2.4	-3.0
¾-in.	-0.4	-0.4	-0.5	-0.7	-0.9	-1.1	+2.6	+2.1	+1.2	+0.1	-0.3	-0.8
⅜-in.	+2.1	+2.0	+1.5	+1.0	+0.4	0	+3.3	+2.1	+2.0	+1.3	+0.8	+0.2
7 SK. PER CU. YD. 5 to 6-IN. SLUMP												
1½-in.	-1.3	-1.4	-1.7	-1.9	-2.0	-2.2	-3.3	-3.3	-3.6	-3.8	-4.0	-4.2
¾-in.	0	-0.3	-0.8	-1.3	-1.5	-1.8	-2.5	-2.3	-2.7	-2.8	-3.0	-3.0
⅜-in.	-0.5	-0.4	-0.9	-1.2	-1.4	-1.7	-0.7	-0.7	-0.9	-1.3	-1.7	-2.0

TABLE 10

LENGTH AND WEIGHT CHANGES OF CONCRETES PRIOR TO FREEZING AND THAWING

Cement content: 4sk. per cu. yd. Slump: 5 to 6 inches.
Specimen size: 3 by 3 by 11¼-in. prisms.

Ref. No.	Net W/C, gal. per sk.	Air Content, % Pressure	Length Changes During Periods Indicated -%			Weight Changes During Periods Indicated -%		
			14d. Moist (+)	14d. Air (-)	3d. in Water (+)	14d. Moist (+)	14d. Air (-)	3d. in Water (+)
MAXIMUM SIZE OF AGGREGATE - 1½-IN.								
301	8.35	2.37	.014	.028	.019	0.6	3.9	3.3
302	7.67	5.01	.012	.030	.021	0.8	3.9	3.3
303	7.22	6.94	.011	.029	.020	0.9	3.6	2.9
304	6.84	8.45	.011	.030	.021	1.0	3.5	2.8
305	6.41	11.15	.012	.032	.021	1.2	3.5	2.7
MAXIMUM SIZE OF AGGREGATE - ¾-IN.								
306	9.23	3.37	.011	.031	.022	0.7	4.9	4.4
307	8.37	6.40	.012	.032	.022	0.9	4.5	4.0
308	7.86	8.53	.012	.034	.023	1.1	4.3	3.6
309	7.45	10.20	.012	.034	.023	1.2	4.2	3.5
310	6.73	12.99	.012	.036	.024	1.5	4.0	3.1
MAXIMUM SIZE OF AGGREGATE - ⅜-IN.								
311	10.26	5.83	.015	.040	.028	0.9	6.3	5.7
312	9.30	8.60	.011	.040	.027	1.2	5.9	5.2
313	8.67	10.83	.013	.042	.028	1.3	5.5	4.9
314	7.90	13.13	.013	.044	.029	1.5	5.2	4.5
315	7.27	16.00	.012	.046	.029	1.8	5.2	4.2

These data regarding air void characteristics, freezable water and length changes will be presented in a future report.

DISCUSSION OF RESULTS

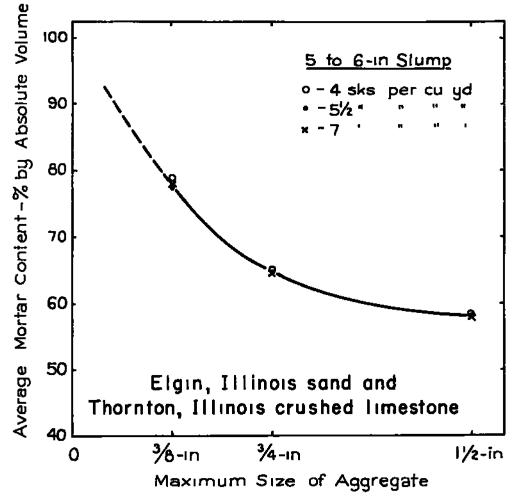


Figure 1. Relationship Between Maximum Size of Aggregate and Mortar Content for Concretes of Constant Cement Content and Consistency.

Characteristics of Concretes

Tables 6, 7 and 8 show data on the concrete mixes used in these tests. Figure 1 shows the changes in mortar content resulting from changes in maximum size of aggregate in mixes of constant cement content and consistency.

Figure 2 shows the changes in air content with changes in maximum size of aggregate and the average mortar content for each size of aggregate.

The water requirements of the concretes as a function of entrained air, for each maximum size of aggregate, are shown in Figure 3.

Effect of Entrained Air on Concrete Strength

Flexural and compressive strength data are shown in Tables 6, 7 and 8 and in Figure 4, 5 and 6.

Table 9 summarizes the results of the strength tests and shows the average percentage change in strength for each one percent of intentionally entrained air up to 6 percent

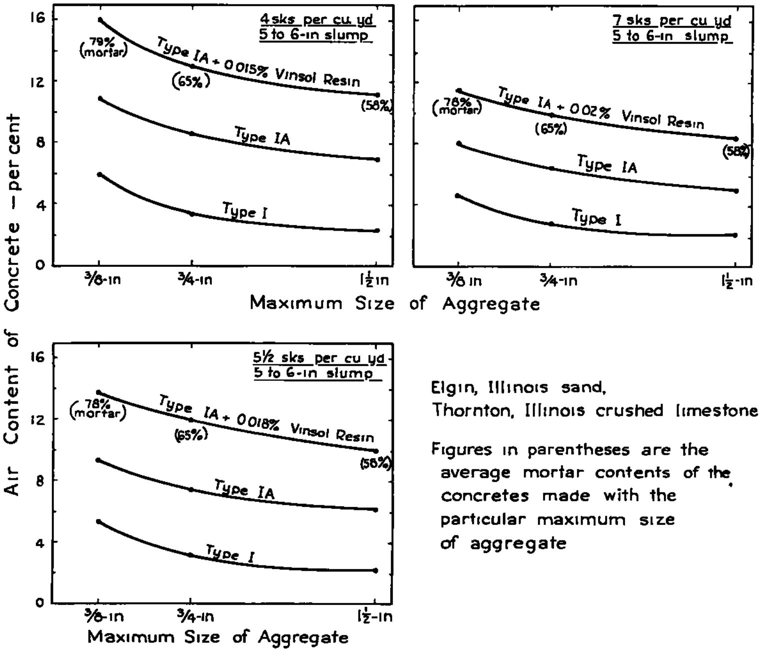
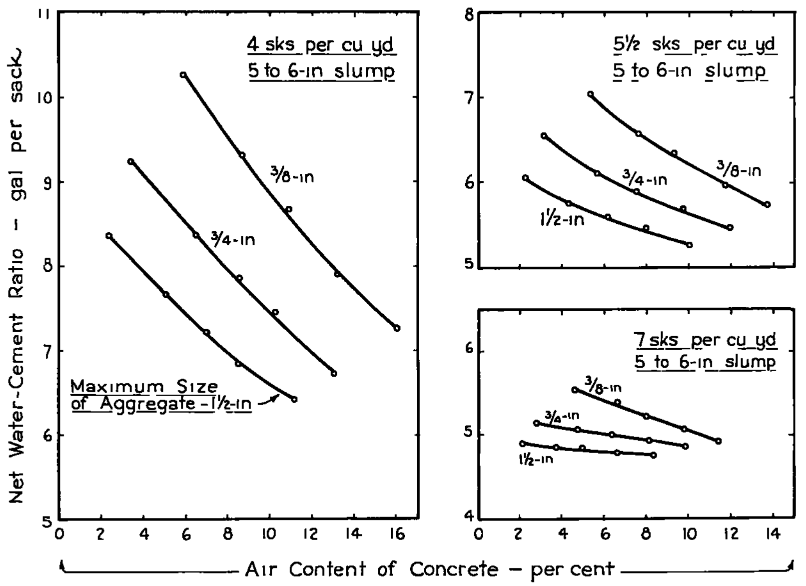


Figure 2. Relationships Between Maximum Size of Aggregate and Air Content for Concretes of Constant Cement Content and Consistency.

(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-strength relationships shown in Figures



Elgin, Illinois sand and
Thornton, Illinois crushed limestone

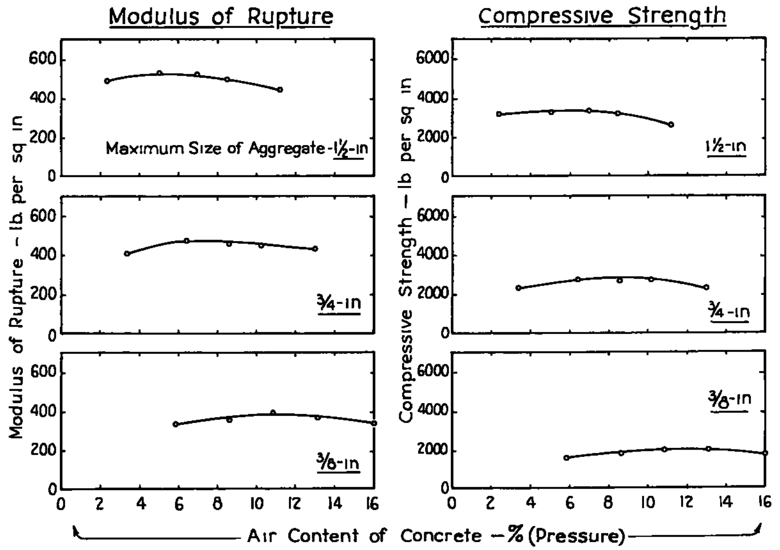
Figure 3. Effect of Air Content on the Water Requirement of Concretes of Constant Cement Content and Consistency Made With Various Maximum Sizes of Aggregate.

TABLE 11

LENGTH AND WEIGHT CHANGES OF CONCRETES PRIOR TO FREEZING AND THAWING

Cement content: 5½ sk. per cu. yd. Slump: 5 to 6 inches.
Specimen size: 3 by 3 by 11¼-in. prisms.

Ref. No.	Net W/C. gal. per sk.	Air Content, % Pressure	Length Changes During Periods Indicated-%			Weight Changes During Periods Indicated-%		
			14d. Moist (+)	14d. Air (-)	3d. in Water (+)	14d. Moist (+)	14d. Air (-)	3d. in. Water (+)
MAXIMUM SIZE OF AGGREGATE -1½-IN.								
316	6.04	2.25	.006	.028	.020	0.6	2.9	2.2
317	5.75	4.29	.006	.028	.021	0.7	2.7	2.1
318	5.60	6.15	.006	.028	.022	0.8	2.7	2.0
319	5.47	7.90	.006	.031	.023	0.9	2.8	2.1
320	5.26	10.03	.008	.031	.023	1.2	2.8	2.1
MAXIMUM SIZE OF AGGREGATE - ¾-IN.								
321	6.55	3.15	.013	.034	.024	0.7	3.5	2.6
322	6.10	5.60	.011	.036	.025	0.9	3.3	2.4
323	5.88	7.44	.010	.038	.026	0.9	3.1	2.2
324	5.68	9.77	.010	.039	.026	1.2	3.1	2.3
325	5.46	11.95	.010	.038	.026	1.3	3.2	2.2
MAXIMUM SIZE OF AGGREGATE - ⅜-IN.								
326	7.03	5.28	.009	.041	.027	0.8	4.1	3.2
327	6.57	7.55	.011	.043	.028	0.9	3.9	2.9
328	6.34	9.30	.013	.044	.029	1.1	3.8	2.8
329	5.97	11.75	.012	.045	.029	1.3	3.7	2.5
330	5.73	13.70	.012	.048	.031	1.5	3.8	2.5



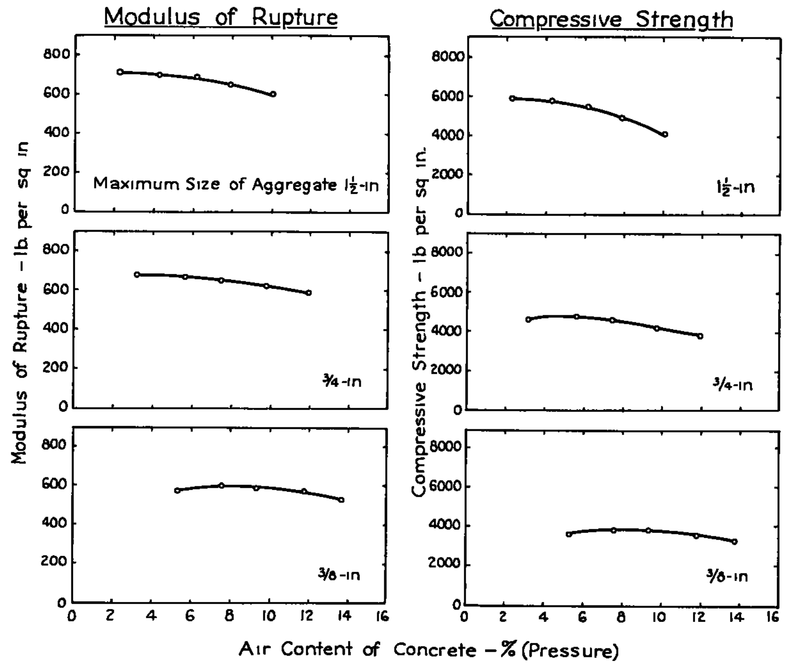
Cement Content 4sks per cu yd Slump 5 to 6 inches
Aggregate Elgin, Ill sand and Thornton, Ill crushed limestone
Cements Type I, Type IA, and Type IA + neutralized Vinsol resin
Curing Continuously moist Compression 6-in modified cubes
Flexure 6 x 6 x 30-in beams, third point loading on an 18-in span

Figure 4. Effect of Entrained Air on the 28-day Strength of Concretes of Constant Cement Content and Consistency Made With Various Maximum Sizes of Aggregate.

TABLE 12
LENGTH AND WEIGHT CHANGES OF CONCRETES PRIOR TO FREEZING AND THAWING

Cement content: 7sk. per cu. yd. Slump: 5 to 6 inches.
Specimen size: 3 by 3 by 11¼-in. prisms.

Ref. No.	Net W/C, gal. per sk.	Air Content, % Pressure	Length Changes During Periods Indicated-%			Weight Changes During Periods Indicated-%		
			14d. Moist (+)	14d. Air (-)	3d. in. Water (+)	14d. Moist (+)	14d. Air (-)	3d. in. Water (+)
		MAXIMUM SIZE OF AGGREGATE-1½-IN.						
331	4.90	2.16	.008	.028	.020	0.8	2.2	1.6
332	4.87	3.68	.008	.030	.024	0.9	2.3	1.6
333	4.86	4.99	.008	.030	.022	0.9	2.3	1.6
334	4.79	6.65	.009	.031	.021	1.0	2.4	1.7
335	4.77	8.38	.009	.033	.022	1.1	2.5	1.8
		MAXIMUM SIZE OF AGGREGATE-¾-IN.						
336	5.15	2.77	.008	.035	.023	0.8	2.4	1.7
337	5.08	4.73	.010	.036	.024	0.8	2.4	1.8
338	5.01	6.35	.006	.036	.025	0.9	2.4	1.7
339	4.94	8.10	.006	.039	.026	1.0	2.4	1.8
340	4.87	9.87	.008	.040	.027	1.2	2.6	1.8
		MAXIMUM SIZE OF AGGREGATE-⅜-IN.						
341	5.55	4.57	.010	.041	.027	0.9	3.0	2.1
342	5.40	6.70	.010	.044	.029	1.0	3.0	2.1
343	5.23	7.96	.011	.045	.029	1.0	2.8	1.9
344	5.08	9.78	.010	.046	.030	1.0	2.7	1.9
345	4.93	11.40	.011	.048	.031	1.2	2.8	1.9



Cement Content 5½ sks per cu yd Slump 5 to 6 inches
Aggregate Elgin, Ill sand and Thornton, Ill crushed limestone
Cements Type I, Type IA, and Type IA + neutralized Vinsol resin
Curing Continuously moist Compression 6-in modified cubes
Flexure 6 x 6 x 30-in beams, third point loading on an 18-in span

Figure 5. Effect of Entrained Air on the 28-day Strength of Concretes of Constant Cement Content and Consistency Made With Various Maximum Sizes of Aggregate.

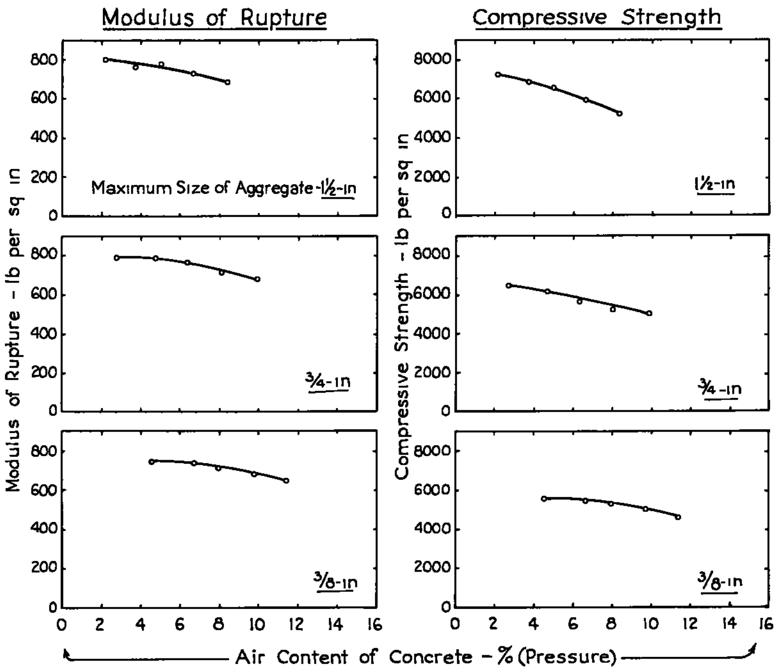
TABLE 13

RESULTS OF SURFACE SCALING AND FREEZING AND THAWING TESTS - 4 SK. PER CU YD

See text for description of test specimens and procedure Three specimens per reference number
Cement content of concretes - 4 sk. per cu yd. Slump· 5 to 6 inches
Elgin, Illinois, sand and Thornton, Illinois crushed limestone
Curing· 14 days moist, 14 days in air and 3 days in water prior to start of tests.

Ref No	Air Content, % Pressure	Rating of Slab Surface After 125 Cycles of F & T	Expansion, Change in Dynamic E and Wt. Loss During 300 Cycles of F & T			No. of Cycles of F & T. for 0.10% Expansion
			% Expansion	% Change in E	% Wt. Loss	
MAXIMUM SIZE OF AGGREGATE - 1½-IN.						
301	2.37	(85)[a]	(95)[a]	(95)	(95)	60
302	5.01	0+	0 023	-7	5.7	076 at 800 Cycles
303	6.94	0+	0.019	+2	1.4	048% " " "
304	8.45	0+	0 020	+3	0.7	052% " " "
305	11.15	0+	0.024	+3	0 8	.069% " " "
MAXIMUM SIZE OF AGGREGATE-¾-IN.						
306	3 37	(70)	(70)	(70)	(70)	47
307	6 40	0+	0 030	-20	9 2	565
308	8 53	0+	0.019	+1	2.1	049% at 800 cycles
309	10.20	0+	0.021	+2	1.1	054% " " "
310	12.99	0+	0 023	+2	0.7	.064% " " "
MAXIMUM SIZE OF AGGREGATE-⅜-IN.						
311	5.83	(65)	(70)	(70)	(70)	39
312	8.60	1+	0.027	-27	12 6	825
313	10.83	1-	0 020	-5	4.4	054% at 800 cycles
314	13.13	1-	0 020	-1	2.1	052% " " "
315	16 00	1-	0.021	-2	1.8	.053% " " "

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



Cement Content 7 sks per cu yd Slump 5 to 6 inches
Aggregate Elgin, Ill sand and Thornton, Ill crushed limestone
Cements Type I, Type IA, and Type IA + neutralized Vinsol resin
Curing Continuously moist Compression 6-in modified cubes
Flexure 6 x 6 x 30-in beams, third point loading on an 18-in span

Figure 6. Effect of Entrained Air on the 28-day Strength of Concretes of Constant Cement Content and Consistency Made With Various Maximum Sizes of Aggregate.

TABLE 14

RESULTS OF SURFACE SCALING AND FREEZING AND THAWING TESTS - 5½ SK PER CU YD.

See text for description of test specimens and procedure Three specimens per reference number
Cement content of concretes - 5½ sk. per cu. yd Slump 5 to 6 inches.
Elgin, Illinois, sand and Thornton, Illinois, crushed limestone
Curing: 14 days moist, 14 days in air and 3 days in water prior to start of tests.

Ref No	Air Content, % Pressure	Rating of Slab Surface After 125 cycles of F. & T.	Expansion, Change in Dynamic E and Wt. Loss During 300 cycles of F & T			No of cycles of F. & T for 0.10% Expansion
			% Expansion	% Change in E	% Wt. Loss	
			MAXIMUM SIZE OF AGGREGATE - 1½-IN.			
316	2.25	(110)[a]	(175)[a]	(175)	(175)	125
317	4.29	0+	0.029	+3	0.3	.069% at 800 cycles
318	6.15	0+	0.027	+4	+0.2	.057% " " "
319	7.90	0+	0.026	+5	+0.6	.054% " " "
320	10.03	0+	0.029	+3	+0.7	.068% " "
			MAXIMUM SIZE OF AGGREGATE - ¾-IN			
321	3.15	4	(225)	(225)	(225)	175
322	5.60	0+	0.027	0	0.9	.064% at 800 cycles
323	7.44	0+	0.023	+5	+0.1	.049% " " "
324	9.77	0+	0.024	+3	+0.3	.052% " " "
325	11.95	0+	0.024	+3	+0.3	.056% " " "
			MAXIMUM SIZE OF AGGREGATE - ⅜-IN			
326	5.28	4-	0.230	-75	16.8	225
327	7.55	0+	0.025	+2	0.4	.062% at 800 cycles
328	9.30	0+	0.021	+4	0	.048% " " "
329	11.75	0+	0.021	+5	+0.2	.044% " " "
330	13.70	0+	0.020	+4	+0.3	.043% " " "

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

TABLE 15

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

See text for description of test specimens and procedure. Three specimens per reference number.
Cement content of concretes - 7 sk. per cu. yd. Slump: 5 to 6 inches.
Elgin, Illinois, sand and Thornton, Illinois, crushed limestone.
Curing: 14 days moist, 14 days in air and 3 days in water prior to start of of tests.

Ref. No.	Air Content, % Pressure	Rating of Slab Surface After 125 Cycles of F. & T.	Expansion, Change in Dynamic E and Wt. Loss During 300 Cycles of T. & T.			No. of Cycles of F. & T. for 0.10% Expansion
			% Expansion	% Change in E	% Wt. Loss	
MAXIMUM SIZE OF AGGREGATE - 1½-IN.						
331	2.16	4	(100)[a]	(100)	(100)	62
332	3.68	0+	0.043	-2	0.1	560
333	4.99	0	0.034	+4	+0.3	.070% at 800 cycles
334	6.65	0	0.031	+2	+0.4	.063% " " "
335	8.38	0	0.031	+4	+0.7	.061% " " "
MAXIMUM SIZE OF AGGREGATE - ¾-IN.						
336	2.77	2+	(125)	(125)	(125)	100
337	4.73	0+	0.036	+1	0.4	.083% at 800 cycles
338	6.35	0+	0.028	+3	+0.1	.057% " " "
339	8.10	0+	0.028	+4	+0.5	.053% " " "
340	9.87	0	0.027	+4	+0.6	.051% " " "
MAXIMUM SIZE OF AGGREGATE - ⅜-IN.						
341	4.57	2	(240)	(240)	(240)	170
342	6.70	0+	0.034	+2	0.3	.076% at 800 cycles
343	7.96	0+	0.026	+4	+0.4	.053% " " "
344	9.78	0+	0.025	+3	+0.5	.048% " " "
345	11.40	0+	0.023	+4	+0.7	.044% " " "

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

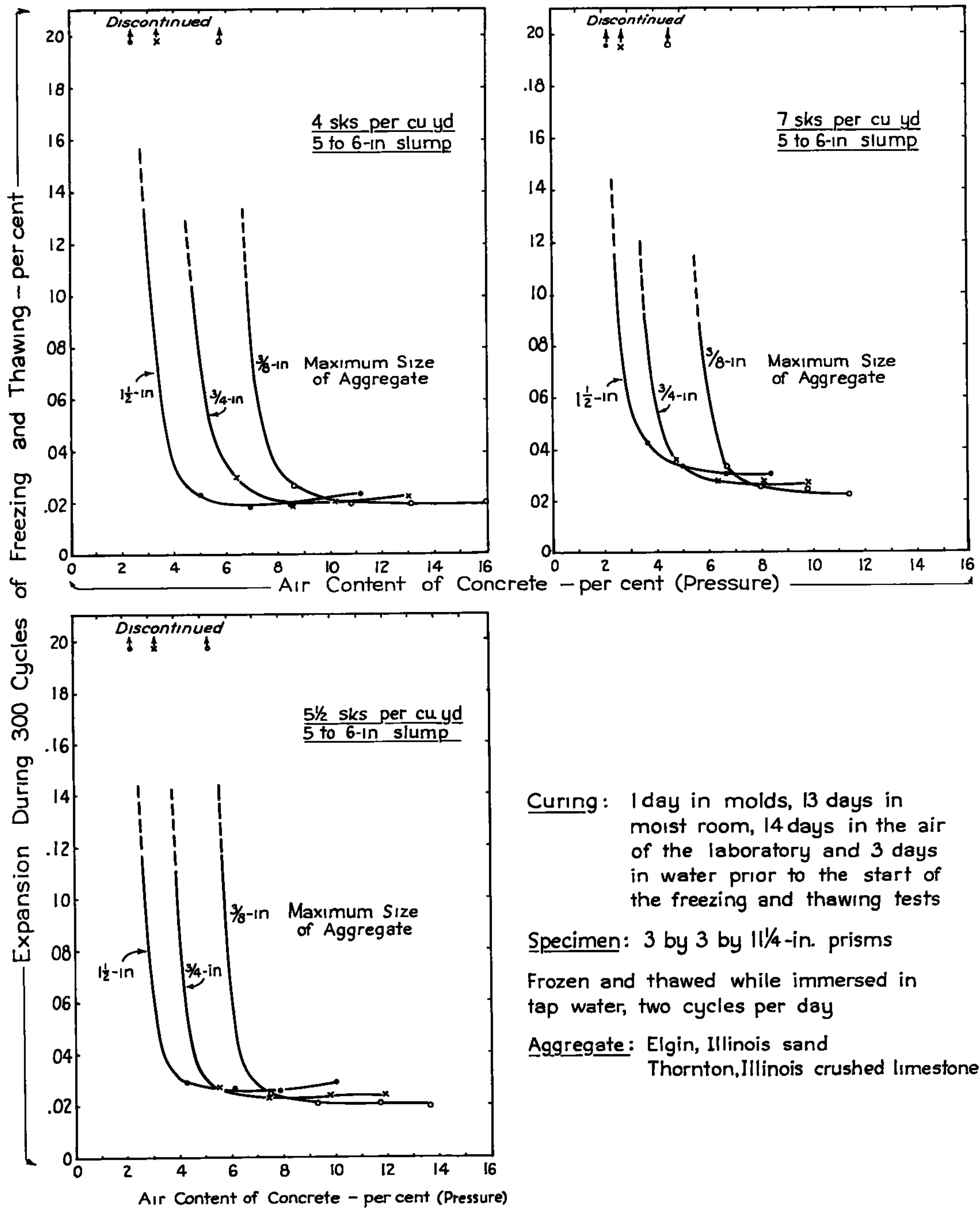
4, 5 and 6, using the strength of the non-air entrained concrete in each group as the reference strength.

The data shown in Table 9 indicate that all of the 4-sk. concretes showed increases in strength with entrainment of up to 6 percent additional air. In these mixes, the reductions in water requirement with entrainment of air were large enough to offset the effect of the entrained air on the strength. The 5½-sk. concretes made with the ⅜-in. aggregate showed strength increases. In the remainder of the 5½-sk. and all of the 7-sk. mixes, the entrainment of air resulted in small decreases in strengths. The greater reductions in water requirement effected by the entrained air as the size of aggregate was decreased resulted in less of a decrease in strength for these mixes.

The maximum air contents used in these tests were well above those which would ordinarily be used in practice on well controlled jobs. These higher air contents were used to aid in establishing trends revealed by the data.

Effect of Entrained Air on Length and Weight Changes During Curing

Tables 10, 11 and 12 show the length and weight changes of the freezing and thawing prisms determined during the curing period consisting of 14 days moist, 14 days in the air of the laboratory and 3 days in water prior to the start of freezing and thawing tests.



Curing: 1 day in molds, 13 days in moist room, 14 days in the air of the laboratory and 3 days in water prior to the start of the freezing and thawing tests

Specimen: 3 by 3 by 11¼-in. prisms

Frozen and thawed while immersed in tap water, two cycles per day

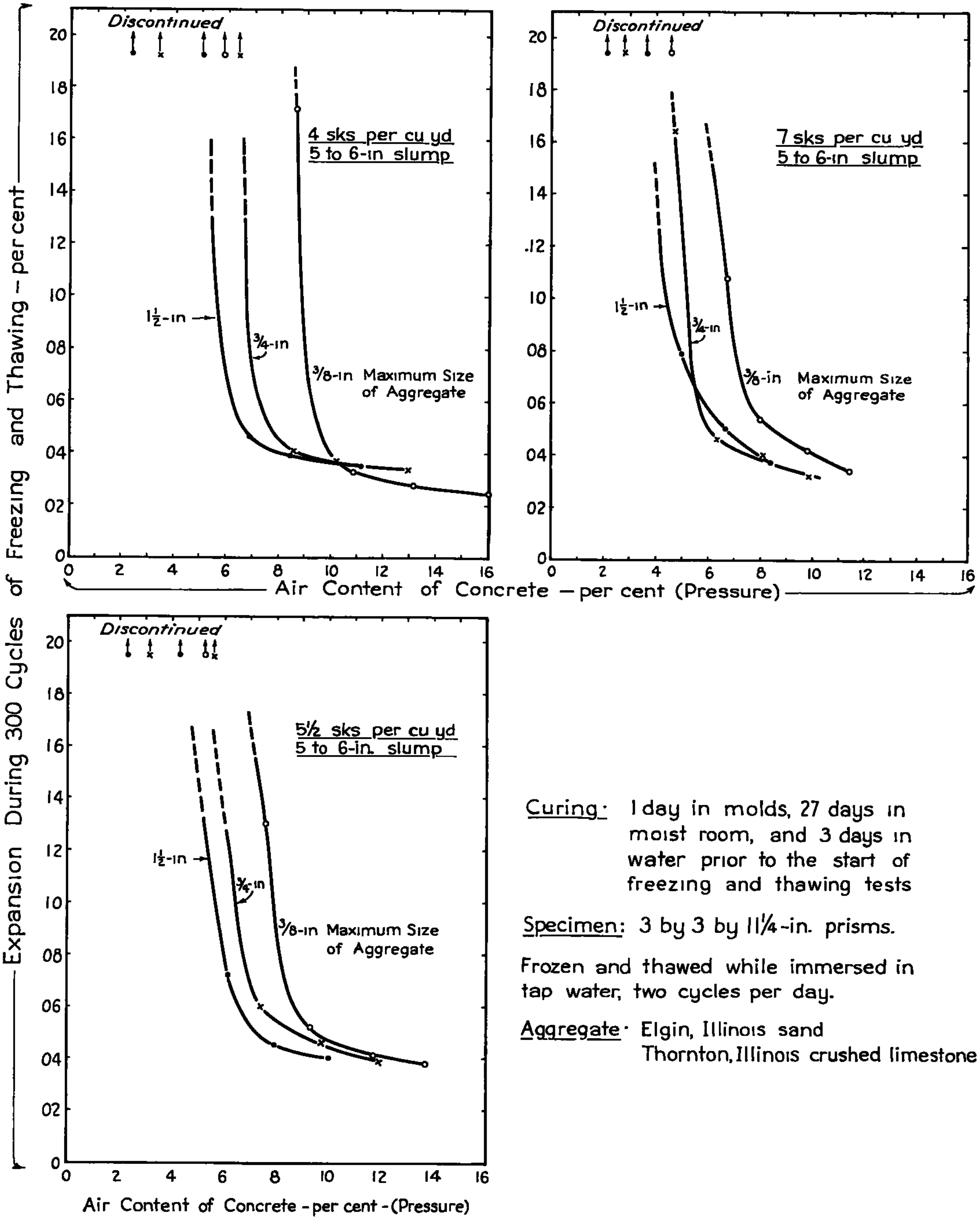
Aggregate: Elgin, Illinois sand
Thornton, Illinois crushed limestone.

Figure 7. Expansion of Concretes During 300 Cycles of Freezing and Thawing.

As in the first series of tests, there appears to be no significant effect of entrained air on the length changes during the initial 14 days of moist storage, a slight increase in contraction with increase in air content during the following 14 days in the air and only a slight trend toward increased expansion with increase in air content during the 3 days storage in water.

All of the concretes showed increasing weight gains with increase in air content

during the initial 14 days of moist storage. During the 14 days in the air of the laboratory, none of the concretes showed any signigicant differences in loss of water with



Curing: 1 day in molds, 27 days in moist room, and 3 days in water prior to the start of freezing and thawing tests

Specimen: 3 by 3 by 11¼-in. prisms.

Frozen and thawed while immersed in tap water, two cycles per day.

Aggregate: Elgin, Illinois sand
Thornton, Illinois crushed limestone

Figure 8. Expansion of Concretes During 300 Cycles of Freezing and Thawing.

air content. In general the absorptions decreased slightly for all concretes with increase in air content.

Effect of Entrained Air on Resistance to Freezing and Thawing of Concretes

Tables 13, 14 and 15 show the expansions, changes in dynamic modulus and changes in weight for the air-dried concretes during 300 cycles of freezing and thawing. Concretes in the first series of tests were also compared as to durabilities during 300 cycles. In addition, where available, the number of cycles for 0.10 percent expansion are also shown. Where the specimens have not yet reached 0.10 percent expansion, the latest available expansion data are presented.

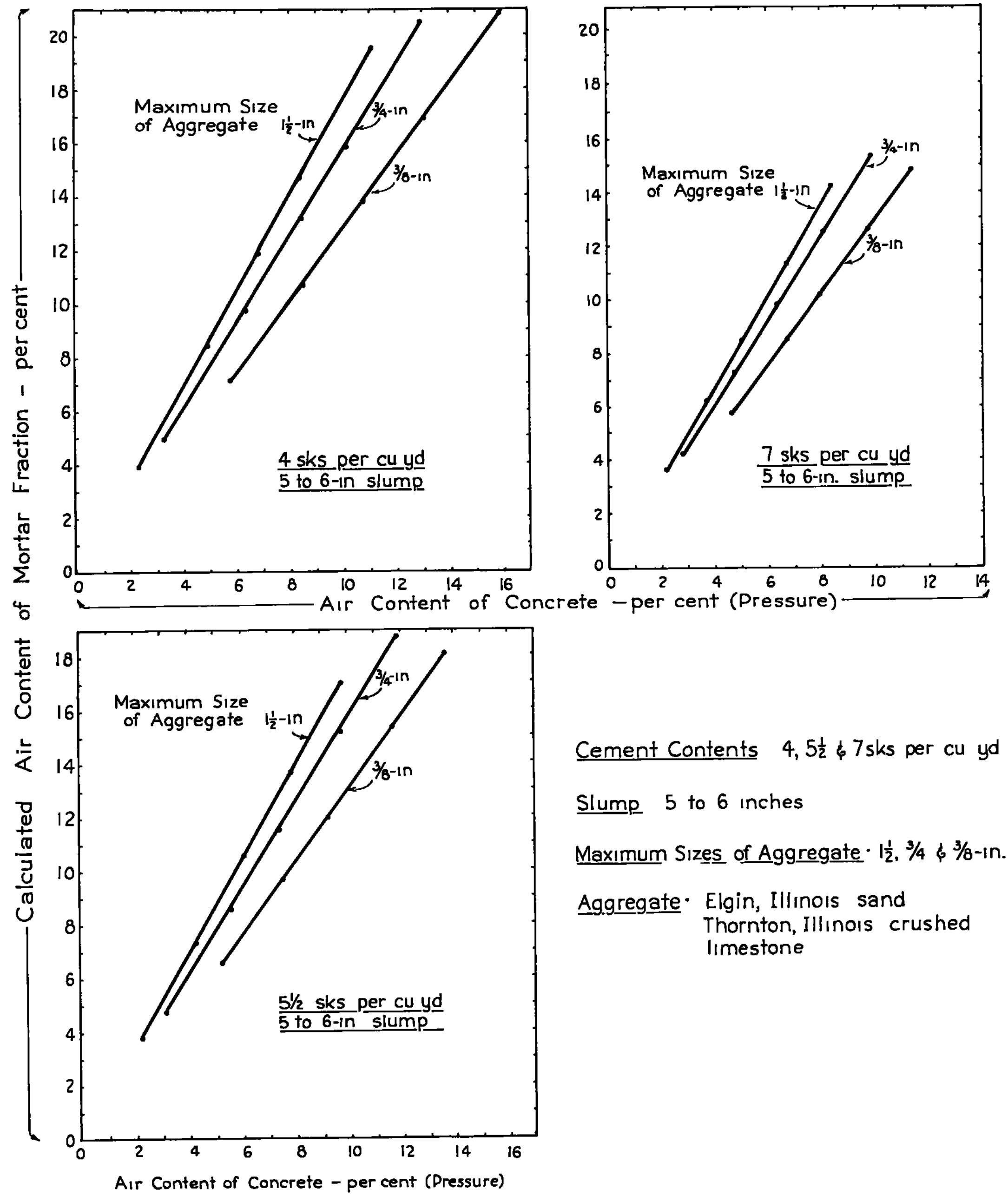


Figure 9. Relationships Between Air Content of Concrete and Calculated Air Content of Mortar Fraction.

Figure 7 shows the expansion during the 300 cycles of freezing and thawing as a function of the air content of the air-dried concretes. Figure 8 shows the same relationships for the continuously moist-cured concretes. For both curing conditions, the resistance to freezing and thawing increased greatly as the air content was increased to some particular level. Further increases in air showed no commensurate further increase in durability, particularly for the air-dried concretes. This level of air content was defined in the first report on this study as that minimum air content beyond which further increases in air result in only a marginal decrease in expansion and is therefore considered to be a balance point between increase in durability and reduction in strength. This air content has been termed the optimum concrete air content.

Table 16 shows the optimum concrete air contents for the air dried concretes as determined visually from Fig. 7. More emphasis is placed on the results of tests of the air-dried concretes than those of the continuously moist-cured concretes, since practically all concrete in service undergoes some drying during its early life. This drying is generally beneficial with regard to resistance of the concrete to freezing and thawing action.

TABLE 16

CHARACTERISTICS OF CONCRETES AT OPTIMUM AIR CONTENTS

Elgin, Illinois, sand and Thornton, Illinois, crushed limestone.
Optimum concrete air contents determined visually from Figure 7.
Air contents of mortar fractions calculated and shown in Figure 9.[a]
Air contents of paste fractions calculated.[a]

Maximum Size of Aggregate, in.	Air Content of concrete Made With Type IA Cement, %	Data for Optimum Concretes		
		Optimum Concrete Air, %	Air in Mortar Fraction %	Air in Paste Fraction, %
		4 SK. PER CU. YD.		
1½	6.9 (5.8)[b]	5.0 (4.5)	8.5 (8.3)	18.2 (18.2)
¾	8.5 (7.4)	6.5 (5.5)	10.0 (8.9)	21.5 (19.8)
⅜	10.8 (9.6)	8.0 (8.5)	10.0 (11.1)	23.4 (26.2)
		5½ SK. PER CU. YD.		
1½	6.2 (4.0)	5.0 (4.5)	8.6 (8.5)	16.6 (16.4)
¾	7.4 (5.6)	6.0 (5.0)	9.2 (8.3)	18.6 (16.9)
⅜	9.3 (8.3)	7.5 (6.5)	9.6 (8.7)	21.2 (19.7)
		7 SK. PER CU. YD.		
1½	5.0 (2.9)	5.0 (4.5)	8.5 (8.4)	14.5 (14.3)
¾	6.4 (4.3)	6.0 (5.5)	9.2 (9.2)	16.4 (16.8)
⅜	8.0 (6.9)	7.5 (7.0)	9.6 (9.6)	19.4 (19.4)

[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.

[b] Figures in parentheses are the data obtained in the first series of tests using a crushed gravel as the coarse aggregate.

The optimum concrete air contents shown in Table 16 are, for a particular maximum size of aggregate, practically the same for each of the three cement contents. At the same cement content, the optimum concrete air content increases with a decrease in the maximum size of aggregate.

These optimum concrete air contents may be used to determine the air contents of the mortar fraction by means of the relationships in Figure 9. Table 16 shows these mortar fraction air contents and it can be seen that they fall in the range of 9 ± 1 percent of air, the same range determined in the first series of tests using a different coarse aggregate and concrete at a lower slump. The calculated paste air contents are also shown in this table, but while the mortar fraction air contents for the optimum concretes are relatively stable, the air requirements of the paste increase with a decrease in maximum size of aggregate. The method used to calculate the air contents of the mortar and paste fractions is shown in Table 16.

It appears from these data and the data obtained in the first report (shown in parentheses in Table 16) that 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 amount of air in the mortar fraction, despite changes in cement content, maximum size of aggregate, consistency and probably types of aggregate. These tests were made with two types of coarse aggregate and two concrete consistencies.

The optimum concrete air contents for these limestone concretes were from ½ to 1 percentage points higher than those for the gravel concretes in the first series of tests. This resulted from the higher mortar contents of the limestone concretes.

The continuously moist-cured concretes, although showing considerable increase in durability with entrainment of air, apparently require more air for the same degree of durability than do the air-dried concretes (See Figure 8). This difference in air requirements was less pronounced as the cement content was increased from 4 to 7 sk. per cu. yd.

The Role of Type IA Cement in Providing Optimum Air Contents

In the first series of tests the Type IA cement in most cases produced as much or slightly more than the amount of air indicated to be necessary. In these tests, the air contents produced by the Type IA, shown in Table 16, were in every case equal to or somewhat greater than the indicated optimum concrete air contents, despite changes in maximum size of aggregate and cement content.

At the concrete air contents produced by the Type IA cement, the resistance to freezing and thawing for all of the moist-cured concretes in these tests during 300 cycles of test is considered satisfactory based on the expansion-air content relationships shown in Figure 8.

Effect of Entrained Air on Resistance to Surface Scaling

Tables 13, 14 and 15 also show the results of tests for resistance to surface scaling resulting from the use of calcium chloride for ice removal.

All of the concretes with intentionally entrained air showed excellent resistance to surface scaling, with the possible exception of the 4-sk. concrete made with the ⅜-in. maximum size of aggregate, although even in this case the improvement in scale resistance was great.

GENERAL OBSERVATIONS

This second series of tests has produced what might be considered excellent confirmation of the conclusion reached in the first series of tests reported on earlier, namely that despite changes in cement content, maximum size of aggregate, consistency and type of coarse aggregate a relatively constant amount of air in the mortar fraction in the range of 9 ± 1 percent will provide the optimum air content in concrete. These observations with regard to optimum concrete air content and air content of the mortar fraction should apply to concretes showing the normally occurring distribution of air void sizes, a situation which will in general prevail. There may be instances where an abnormal distribution of air void sizes will limit the practical usefulness of this criterion. However, it is believed that these occurrences will be few in actual practice.

This information provides a practical approach to the problem of specifying the amount of air required for adequate resistance to frost action by specifying merely the air content of the mortar fraction. Based on the desired mix proportions, this mortar air content may then be converted to concrete air content. Control of actual mixing operations would then center about this concrete air content.

At this time, there appears to be no special theoretical significance to ascribe to the utility of the 9 ± 1 percent mortar fraction air content in producing frost-resistant concrete.

Continued efforts are being made to determine the basic factors controlling the resistance of concrete to freezing and thawing. Previous tests indicated the importance of the air void characteristics, such as bubble spacing, and the influence of the amount of water actually freezing within the concrete. Data of this type are now being obtained for these concretes and the evaluation of these data will constitute a future report. The next phase of this study will place emphasis on the effect of concrete temperature during mixing on the air void characteristics together with the effect of different curing temperatures on the freezable water characteristics of the concretes. These data will then be correlated with actual laboratory freezing and thawing data. Further studies will include the effect of vibration, mixing time, sand grading and other variables.

SUMMARY

Based on both these recent tests and the first series of tests reported previously, the following observations and conclusions appear pertinent. Many of these have been made as a result of prior tests[3] and tests by other investigators, but appear worthy of repetition. These conclusions were derived from concretes made and cured at normal temperature (73° F.) and having a normally occurring distribution of air void sizes such as produced by the commonly accepted air-entraining agents.

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 reduction in water requirements possible in the leaner mixes. These larger reductions in water requirements often result in increases in strength as air is entrained in the lean mixes.
3. There appears to be no significant effect of air content on volume change or weight change during moist storage or air storage, or on absorption during 3 days 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 concrete air requirement for frost resistance increased as the maximum size of aggregate decreased.
6. For the air-dried concretes at a particular maximum size of aggregate there appears to be little effect of cement content on the optimum concrete air content.
7. For the air-dried concretes, the tests indicate that the optimum concrete air content can be obtained by providing a relatively constant air content in the mortar fraction, despite changes in cement content, consistency, maximum size of aggregate or type of aggregate. This mortar air content appears to be in the range of 9 ± 1 percent.
8. Concretes cured continously moist required more entrained air for adequate resistance to freezing and thawing than the air-dried concretes. The Type IA cement provided a sufficiently high level of air content for these concretes.
9. For any given cement, the use of a constant amount of air-entraining agent per unit of cement appears to provide a self-regulating means for obtaining optimum concrete air contents despite variations in the proportions of concrete mix constituents and changes in the type of aggregate.

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[3] "Effect of Entrained Air Strength and Durability of Concrete Made With Various Maximum Sizes of Aggregate" by Paul Klieger, Bulletin 40, Portland Cement Association, Chicago, Illinois.