Supplementary Report on Tests of Concrete Containing Portland Blast-Furnace Slag Cement

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This report includes the data contained in a previous report plus tests made at a later age and tests on concrete containing another water-cement ratio. In general these tests show good results for concrete containing portland blast-furnace slag cements. Air-entraining concrete containing type IS cements gave lower compressive and flexure strengths at 3 and 7 days, equal at 28 days, and higher at 90 days and one year than corresponding concretes containing type I cements. Some improvement in durability was also noted.

• A PRELIMINARY report (*1, 2*) in 1957 included the results of all tests which had been completed at that time. Data were presented on the physical properties of air-entrained concretes prepared with five type I and five type IS portland blast-furnace slag cements from five cement plants. Portland blast-furnace slag cement is defined as an intimately interground mixture of portland cement clinker and granulated blast-furnace slag. The same clinker was used in the manufacture of the portland cement and the portland blast-furnace cement from the same plant. The data included results of compressive and flexural strengths and sonic moduli of elasticity at ages ranging from 3 through 90 days on moist-cured concretes prepared with 5½, 6½ and 7½ gal of water per bag of cement. Results of strength tests after 28 days of intermittent curing and preliminary data on drying shrinkage and laboratory freezing and thawing tests were given also.

All tests in progress at the time of the report have now been completed. Strength tests have been made through ages of one year for moist-cured specimens and through 90 days for intermittently-cured specimens. Freezing tests were continued through 300 cycles. Volume change measurements were made through a period of one year. Outdoor exposure slabs subjected to natural freezing and thawed with commercial flake calcium chloride were rated for resistance to scaling at the end of two winters.

Tests on a 4½-gal mix were begun and completed after the publication of the preliminary report. This final report contains all data published in the preliminary report plus all data obtained since that time. Additions have been made to the table on the physical and chemical properties of the cements.

MATERIALS AND PROPORTIONS

As stated in the previous report, to avoid repetition of the terms "portland blast-furnace slag cement, type IS" and "portland cement type I," the cements are referred to as slag cement and portland cement, respectively.

TABLE 1
CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF CEMENTS [a]

Characteristic	A I	A IS	B I	B IS	C I	C IS	D I	D IS	E I	E IS
Chemical composition (%):										
Silicon dioxide	20.2	25.0	20.8	26.2	21.1	25.5	21.0	26.7	21.3	26.1
Aluminum oxide [b]	6.0	8.7	5.1	7.8	5.1	6.8	5.6	7.6	5.6	6.7
Ferric oxide	2.8	2.1	3.1	2.3	2.1	1.7	3.3	2.9	3.5	2.4
Calcium oxide	63.4	53.0	63.6	53.6	65.5	59.2	63.4	54.6	62.5	55.7
Magnesium oxide	2.7	3.7	2.8	3.6	2.4	1.8	2.2	3.3	1.7	2.8
Sulfur trioxide	2.3	2.0	1.8	2.3	1.3	1.4	1.9	2.3	2.3	2.2
Loss on ignition	1.5	3.0[c]	1.6	2.0[c]	1.4	2.2[c]	1.2	1.0[c]	1.3	2.2[c]
Sodium oxide	0.08	0.12	0.09	0.09	0.04	0.09	0.10	0.10	0.15	0.15
Potassium oxide	0.36	0.38	0.15	0.20	0.43	0.82	0.17	0.18	1.02	0.91
Equiv. alkalies as Na_2O	0.32	0.37	0.19	0.22	0.32	0.61	0.21	0.22	0.82	0.75
Phosphorus pentoxide [d]	0.10	0.08	0.03	0.02	0.03	0.04	0.09	0.05	0.04	0.03
Manganic oxide	0.53	0.87	0.51	0.85	0.03	0.08	0.29	0.32	0.07	0.50
Sulfide sulfur	0.09	0.56	0.10	0.68	0.01	0.33	0.08	1.04	0.03	0.40
Insoluble residue	0.28	0.57	0.16	0.73	0.22	0.68	0.08	0.20	0.20	0.26
Titanium oxide	0.27	0.44	0.24	0.28	0.28	0.28	0.18	0.20	0.24	0.44
Free lime	0.77	0.26	1.20	0.46	1.60	0.57	0.39	0.19	0.56	0.24
Chlor.-sol. org. sub.	0.003	0.005	0.003	0.006	0.003	0.002	0.003	0.005	0.003	0.008
Calculated compounds (%):										
Tricalcium silicate	54	—	57	—	65	—	51	—	43	—
Dicalcium silicate	17	—	17	—	11	—	22	—	28	—
Tricalcium aluminate	11	—	8	—	10	—	9	—	9	—
Tetracalcium aluminoferrite	8	—	9	—	6	—	10	—	11	—
Calcium sulfate	3.9	—	3.1	—	2.2	—	3.2	—	3.9	—
Merriman sugar test (ml):										
Neutral point	31.4	3.4	17.7	6.9	46.2	19.2	5.5	2.2	8.3	4.2
Clear point	44.9	4.0	23.3	8.0	68.0	26.2	6.2	2.2	9.7	5.3
Calc. sulfate [e] in hardened mortar, as SO_3 (g/l)	—	0.00	—	0.00	0.00	0.00	0.00	—	0.00	0.00
Physical properties:										
Apparent spec. gravity	3.14	2.99	3.12	3.03	3.12	3.05	3.14	3.03	3.14	3.03
Spec. surf., Blaine (cm^2/g)	3810	5000	3325	4820	3425	3775	3680	4040	3555	3605
Passing 325 sieve (%)	92.4	96.0	87.5	97.6	80.0	82.9	94.4	98.2	96.2	94.9
Autoclave expansion (%)	0.10	0.01	0.06	0.00	0.09	0.04	0.07	−0.02	0.04	0.00
Normal consistency (%)	25.2	27.6	23.8	27.2	20.4	22.6	26.6	31.2	26.5	26.6
Time of setting, Gillmore (hr):										
Initial	2.9	2.8	3.7	3.4	1.7	2.6	4.2	3.5	2.9	2.8
Final	5.1	6.8	5.6	6.2	3.4	3.9	6.5	7.9	4.8	6.2
Comp. str. 1:2.75 mortar (psi):										
At 3 days	2700	2555	1620	1730	1960	1740	2635	1740	2465	1525
At 7 days	3860	4170	2625	2630	3440	2940	3940	2750	3525	2360
At 28 days	5645	6120	4150	5190	5145	5120	5615	4615	4965	3900
Tens. str. 1:3 mortar (psi):										
At 3 days	295	290	280	265	265	240	305	265	320	245
At 7 days	365	420	355	335	360	345	390	340	375	315
At 28 days	450	500	450	445	415	425	420	460	435	455
Mortar air content (%)	11.6	8.4	10.4	7.4	8.4	8.1	10.7	8.3	9.4	9.2

False set determ.[f] (mm):										
Initial penetration	50+	50+	50+	50+	50+	50+	50+	5	50+	30
5-min penetration	5	4	50+	7	50+	50+	2	0	32	15
8-min penetration	2	1	50+	4	50+	8	2	0	18	8
11-min penetration	2	1	49	4	50+	3	1	0	14	6
Remix penetration	50+	50+	50+	50+	50+	50+	50+	14	50+	44
False set determ.[g] (mm):										
Initial penetration	36	40+	37	40+	40+	37	40	—	38	36
5-min penetration	18	2	30	18	7	8	31	—	35	34
Drying shrinkage of mortar,[h] 28 days (%)	0.08	0.10	0.08	0.08	0.09	0.10	0.07	0.08	0.09	0.10

[a] All determinations made in accordance with current ASTM methods for portland and portland blast-furnace slag cements.
[b] Corrected for titanium and phosphorus oxides present.
[c] Determined by ASTM Method C 114-58 T, Section 30.
[d] Determined by spectrophotometer method.
[e] Determined by ASTM Method C 265-55 T.
[f] By ASTM Method C 359-55 T.
[g] By Method 2501, Fed. Stand. Spec. No. 158.
[h] By ASTM Method C 340-55 T.

The chemical analyses and physical properties of all cements are given in Table 1, which differs slightly from that given in the previous report as it now includes values for phosphorus pentoxide, titanium dioxide, free lime, and calcium sulfate in hardened mortar. The values for aluminum oxide were corrected for phosphorus pentoxide and titanium dioxide and there are some slight changes in the loss on ignition and in some of the calculated compound values.

Table 1 now also includes the results of tests for the false setting properties of the cements using ASTM Method C 359-55 T and Federal Method 2501 and drying shrinkage tests on mortars using ASTM Method C 340-55 T.

The grading and physical properties of the fine and coarse aggregates used (Table 2) are the same as in the previous report. The mix data (Table 3) correspond with those given in the previous report except that the data for the 4½-gal mix are included.

The mixes were designed on a water-cement ratio basis for air-entrained concrete having 5½ percent air, 2- to 3-in. slump, and b/b_0 of 0.72. The cement contents were approximately 7.5, 6.1, 4.9 and 4.1 bags per cubic yard of concrete for water contents of 4½, 5½, 6½ and 7½ gals per bag of cement. With one exception, the same mix proportions were used for all mixes having the same water content. The exception was the mix containing 6½ gal of water with slag cement from source D. A slight change was made in that mix in order to maintain the desired consistency.

Air was entrained in the concrete by use of a commercial solution of neutralized Vinsol resin. The average amount of air-entraining solution needed for 5½-percent air for the concretes containing the slag cements was the same as was used with

TABLE 2
GRADING AND PHYSICAL PROPERTIES OF THE AGGREGATES

Item	White Marsh Sand	Riverton Limestone
	(a) Grading	
Sieve size:	(% passing)	(% passing)
1 in.	—	100
¾ in.	—	70
½ in.	—	40
⅜ in.	100	24
No. 4	96	0
No. 8	79	—
No. 16	66	—
No. 30	50	—
No. 50	23	—
No. 100	7	—
F. M.	2.79	7.06
	(b) Physical Properties	
Bulk specific gravity:		
Dry	2.63	2.78
S.s.d.	2.65	2.79
Absorption (%)	0.4	0.4
Strength ratio, Ottawa sand (%):		
Comp. 7 days	158	—
Comp. 28 days	167	—
Tension 7 days	106	—
Tension 28 days	116	—
Los Angeles wear test, grading A:		
Loss (%)	—	20.2
Accelerated soundness, Na_2SO_4:		
Loss (%)	—	3.5

the portland cements from sources C and E, 1½ times as much for those from sources A and D, and 2½ times as much for source B.

MIXING, FABRICATING AND CURING OF SPECIMENS

The mixing, molding, curing and testing of test specimens was in accordance with the applicable AASHO or ASTM methods.

During mixing premature stiffening was noted with several of the mixes containing slag cement. Tests had been made in accoradnce with ASTM Method C 359-55 T and Federal Method 2501 to measure this property of the cement. The results are given in Table 1.

The false set is indicated in the ASTM procedure by loss of nearly all of the penetration during the 11-min test period. A difference between initial and final penetration of more than 17 mm after 5 min is considered to be an indication of false set by the Federal method. The two methods can be considered as indicating both types of cement from source A as false setting cements and those from source E as not having false set. Both cements from source C would be considered as equally false setting by the Federal method, but the ASTM method shows only the slag cement from that source as having false set. The slag cement from source D could not be tested properly by either method because a plastic mix could not be prepared with the maximum amount of water permitted. Although the results of these tests are not conclusive, in general there is a greater tendency toward false setting shown for the slag cements than for the corresponding portland cements.

DISCUSSION OF TEST RESULTS

The results of strength tests for the continuously moist-cured specimens and intermittently-cured specimens are given in Tables 4, 5, 6 and 7 and Figures 1, 2 and 3. Data for the sonic and static moduli of elasticity are given in Tables 8 and 9. The average values for drying shrinkage tests are give in Table 10 and Figure 4, and the laboratory freezing-and-thawing data are given in Table 11 and Figure 5. These data are similar to those given in the corresponding tables and figures in the previous report except that these are complete. Additional data are given in two new tables. Table 12 gives the results of tests on concrete slabs subjected to outdoor freezing and subsequent thawing by the use of calcium chloride; Table 13 gives the results of the mortar bar expansion tests for alkali-aggregate reaction.

These data are discussed by com-

TABLE 3

MIX DATA [a] FOR LABORATORY SPECIMENS

Cement		4½ Gal Water per Bag [b]				5½ Gal Water per Bag [b]				6½ Gal Water per Bag [b]				7½ Gal Water per Bag [b]			
Source	Type	Cement Content (bags/cy)	Slump (in.)	Air (%)	V.R. Added (ml/bag)	Cement Content (bags/cy)	Slump (in.)	Air (%)	V.R. Added (ml/bag)	Cement Content (bags/cy)	Slump (in.)	Air (%)	V.R. Added (ml/bag)	Cement Content (bags/cy)	Slump (in.)	Air (%)	V.R. Add (ml/bag)
A	I	7.53	3.0	5.3	30.3	6.07	2.9	5.5	18.8	4.94	2.6	5.4	20.6	4.15	2.1	5.7	20.8
A	IS	7.49	2.9	5.4	44.4	6.06	2.8	5.3	25.2	4.93	2.7	5.6	32.3	4.12	2.3	5.6	32.3
B	I	7.52	3.1	5.4	27.0	6.06	2.9	5.6	15.8	4.93	2.4	5.6	19.7	4.15	2.2	5.4	19.4
B	IS	7.50	2.9	5.3	65.1	6.04	2.7	5.2	38.2	4.91	2.6	5.5	48.3	4.14	2.3	5.2	49.3
C	I	7.50	3.5	5.6	25.5	6.09	3.3	5.4	18.1	4.94	2.4	5.5	20.7	4.16	2.1	5.4	23.2
C	IS	7.50	3.4	5.5	27.0	6.07	3.2	5.5	17.8	4.93	2.2	5.5	22.0	4.14	2.3	5.7	23.2
D	I	7.51	2.7	5.7	29.6	6.07	2.3	5.6	17.7	4.95	2.1	5.4	21.0	4.14	1.9	5.6	21.4
D	IS	7.51	1.9	5.5	56.8	6.06	1.3	5.5	26.5	5.14 [c]	2.0	5.4	29.2	4.15	1.6	5.7	30.7
E	I	7.52	2.9	5.4	28.1	6.09	2.8	5.4	19.3	4.94	2.2	5.5	22.2	4.15	2.0	5.4	23.9
E	IS	7.49	2.6	5.6	37.8	6.06	2.2	5.5	21.6	4.94	2.0	5.3	22.8	4.15	1.8	5.5	24.8

[a] Each value is average of five tests.

[b] Proportions by oven-dry weight except as noted:
4½-gal mix = 94–135–255; 5½-gal mix = 94–190–315; 6½-gal mix = 94–255–390; 7½-gal mix = 94–325–460.

[c] Proportions by oven-dry weight: 94–240–375.

paring the results of tests of concrete containing slag cement with those of concrete containing portland cement. Many of the test data were given in the previous report and are repeated, but in the discussion emphasis is given to the results not covered in the previous report.

Compressive Strength Tests

Results of compressive strength tests of concrete containing portland cements and slag cements from the five sources and moist cured until tested are given in Table 4. Each value is the average of five tests made on 6- by 12-in. cylinders. Mixes containing 4½, 5½, 6½ and 7½ gal of water per bag of cement were tested at ages of 3, 7, 28, 90 and 365 days. The ratios of the strengths of the concretes prepared with the slag cements to the strengths of the concrete prepared with the corresponding portland cements are also given. Comparisons of the average compressive strengths of the concretes prepared with the slag cements from all sources with the concretes prepared with the portland cements for each mix are shown in Figure 1.

Table 4 shows that the concretes prepared with the slag cements from all five sources had lower strengths in most cases at 3 and 7 days than the concretes prepared with the corresponding portland cements. The only exceptions were some of the mixes prepared with the cements from source B. At 28, 90 and 365 days, the concretes prepared with the slag cements from sources A, B, C, and D had greater compressive strengths, in all except three of the 48 cases, than concretes prepared with the portland cements from the same source. Concrete prepared with slag cement from source E had lower compressive strengths at all ages up to and including 90 days than did the corresponding concrete prepared with the portland cement. At 365 days equal or greater strengths were obtained. As shown in Figure 1, the average compressive strengths for concrete prepared with slag cement from all five sources are lower at 3 and 7 days, approximately the same at 28 days, and higher at 90 and 365 days than the compressive strengths of concrete prepared with portland cement.

Flexural Strength Tests

Results of flexural strength tests of concretes prepared with portland cements and slag cements from the five sources and moist cured until tested are given in Table 5. Each value is the average of five tests made on 6- by 6- by 21-in beams. Mixes containing 4½, 5½, 6½ and 7½ gal of water per bag of cement were tested at 3, 7, 28, 90 and 365 days. The ratios of the flexural strengths of the concretes prepared with the slag cements to the flexural strengths of the concretes prepared with the corresponding portland cements are also given. Comparisons of the average flexural strengths of the concretes prepared with the slag cements from all sources with concretes prepared with the portland cements for each mix also are shown in Figure 1.

Approximately the same trends were shown for the flexural strength tests as were shown for the compressive strength tests. In most cases the concretes prepared with the slag cements had lower flexural strengths at 3 and 7 days than the corresponding concretes prepared with the portland cements. The concretes prepared with the slag cements from sources A, B, C, and D had greater flexural strengths at 28, 90 and 365 days than the corresponding portland cement concrete in all cases but one. Concretes prepared with the slag cement from source E had lower strengths at 28 days and equal or greater strengths at 90 and 365 days.

The average flexural strength of the concretes prepared with the slag cements from the five sources (Fig. 1) was lower at 3 and 7 days but higher at 28, 90 and 365 days than that for the concretes prepared with the portland cements.

Effect of Water Content

The relations between the strengths of concretes prepared with the two types of cements were not appreciably affected by changes in water content. At 3, 7, 28 and 90 days there is little difference between the strength ratios for the 4½- and 7½-gal mixes. At 3, 7 and 28 days there is a slight decrease in strength ratios with increases in the water and at 90 days there is a slight increase. At one year the percentage increase in strength of the type IS concrete over the type I concrete becomes greater with each increase in water content. In Figure 2, the ratios of the average strength of the all slag cement concretes at all ages to the average strength of all portland cement concretes at the same ages are plotted against the water content of the concretes. It will be observed that for both compressive and flexural strengths at ages through 90 days there is little difference in the strength ratios for the different mixes. At one year the strength ratios increased as the water content increased. This is interpreted to mean that the ultimate strengths as represented by the strengths at one year of the concrete prepared with slag cement are less subject to changes in water content than the strengths of concrete prepared with portland cement.

Effect of Intermittent Curing on Strength

The effect of intermittent or partial curing on the compressive and flexural strengths of concretes prepared with the portland cements and the slag cements is given in Tables 6

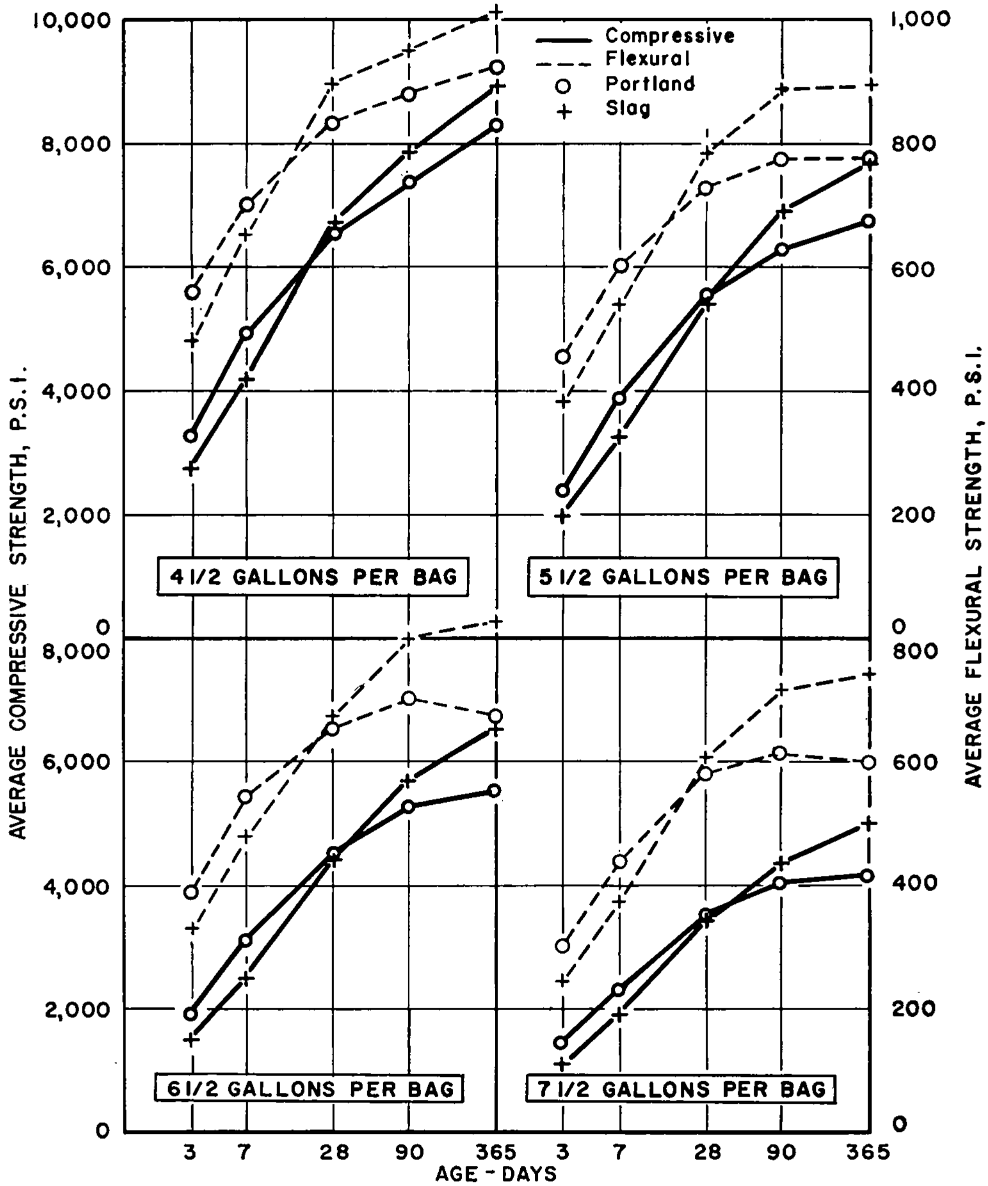

Figure 1. Effect of cement type on compressive and flexural strength of concrete (average of cements from five sources).

and 7, and average values for all cements of a type are shown in Figure 3. One mix, containing 5½ gal of water per bag of cement, was used. Specimens were tested at ages of 28 and 90 days. Three groups of intermittently-cured specimens were tested at 28 days and two at 90 days. The first group was moist cured for 1 day then stored in laboratory air at 73 F and 50 percent relative humidity for 27 days and tested dry.

TABLE 4
COMPRESSIVE STRENGTH TESTS ON MOIST-CURED SPECIMENS [a]

Cement		Compressive Strength (psi)				
Source	Type	3 Days	7 Days	28 Days	90 Days	1 Year
(a) 4½ Gal Per Bag						
A	I	3440	5050	6730	7590	8700
A	IS	3310 (96)	4890 (97)	7370 (110)	8360 (110)	9360 (108)
B	I	2670	4570	6720	7830	8400
B	IS	2800 (105)	4280 (94)	7250 (108)	8870 (113)	9850 (117)
C	I	3010	4770	6060	7040	8080
C	IS	2430 (81)	4240 (89)	6270 (103)	7510 (107)	8430 (104)
D	I	3610	5270	6940	7610	8750
D	IS	2750 (76)	4200 (80)	7210 (104)	8340 (110)	9680 (111)
E	I	3530	5000	6200	6770	7520
E	IS	2480 (70)	3440 (69)	5580 (90)	6290 (93)	7490 (100)
Avg Type I		3250	4930	6530	7370	8290
Avg Type IS		2750 (85)	4210 (85)	6740 (103)	7870 (107)	8960 (108)
(b) 5½ Gal Per Bag						
A	I	2610	4030	5620	6440	6840
A	IS	2340 (90)	3810 (95)	5940 (106)	7140 (111)	7840 (115)
B	I	1940	3330	5400	6380	6730
B	IS	1940 (100)	3020 (91)	5790 (107)	7640 (120)	8490 (126)
C	I	2070	3710	5070	5500	6130
C	IS	1720 (83)	3220 (87)	5320 (105)	6390 (116)	7070 (115)
D	I	2650	4160	6050	6920	7310
D	IS	2110 (80)	3390 (81)	6150 (102)	7600 (110)	8330 (114)
E	I	2680	4150	5660	6240	6820
E	IS	1830 (68)	2790 (67)	4460 (79)	5900 (95)	6740 (99)
Avg all type I		2390	3880	5560	6300	6700
Avg all type IS		1990 (83)	3250 (84)	5530 (99)	6930 (110)	7690 (114)
(c) 6½ Gal Per Bag						
A	I	2050	3260	4670	5440	5590
A	IS	1770 (86)	3060 (94)	4960 (106)	6170 (113)	6910 (124)
B	I	1510	2580	4180	5190	5640
B	IS	1440 (95)	2310 (90)	4560 (109)	6460 (124)	7160 (127)
C	I	1770	2950	4100	4650	4920
C	IS	1360 (77)	2430 (82)	4240 (102)	5030 (108)	5870 (119)
D	I	2180	3400	4970	5780	6110
D	IS	1630 (75)	2440 (72)	4860 (98)	6110 (106)	7060 (116)
E	I	2200	3310	4790	5320	5460
E	IS	1350 (61)	2220 (67)	3680 (77)	4770 (90)	5820 (106)
Avg all type I		1940	3100	4540	5280	5540
Avg all type IS		1510 (78)	2490 (80)	4460 (98)	5710 (108)	6560 (118)
(d) 7½ Gal Per Bag						
A	I	1500	2350	3710	4130	4200
A	IS	1320 (87)	2250 (96)	3780 (102)	4720 (114)	5310 (126)
B	I	1000	1740	2980	3620	3800
B	IS	1070 (107)	1770 (102)	3700 (124)	4970 (137)	5770 (152)
C	I	1320	2240	3250	3640	3820
C	IS	1010 (77)	1810 (81)	3160 (97)	3870 (106)	4350 (114)
D	I	1600	2350	3810	4580	4640
D	IS	1230 (77)	2120 (90)	3670 (96)	4720 (103)	5360 (116)
E	I	1750	2760	3860	4150	4190
E	IS	1010 (58)	1620 (59)	2780 (72)	3600 (87)	4390 (105)
Avg all type I		1430	2290	3520	4020	4130
Avg all type IS		1130 (79)	1910 (83)	3420 (97)	4380 (109)	5040 (122)

[a] Specimens were 6- by 12-in. cylinders stored in moist air until tested, and were capped with neat Lumnite cement. Each value is an average of 5 tests. Figures in parentheses represent ratio of the strength of Type IS to corresponding Type I, in percent.

The second group was moist cured for 1 day, followed by 26 days storage in laboratory air and then immersed in water for 1 day and tested wet. The third group was moist cured for 7 days, followed by 20 days in laboratory air and then immersed in water 1 day.

TABLE 5
FLEXURAL STRENGTH TESTS ON MOIST CURED SPECIMENS [a]

Cement		Flexural Strength (psi)				
Source	Type	3 Days	7 Days	28 Days	90 Days	1 Year
(a) 4½ Gal Per Bag						
A	I	575	700	855	895	955
A	IS	545 (95)	735 (105)	925 (108)	1005 (112)	1090 (114)
B	I	505	680	790	915	910
B	IS	495 (98)	635 (93)	885 (112)	975 (106)	1020 (112)
C	I	500	685	785	780	885
C	IS	460 (92)	705 (103)	955 (122)	915 (117)	950 (107)
D	I	590	705	850	895	955
D	IS	485 (82)	630 (89)	875 (103)	950 (106)	1020 (107)
E	I	595	740	890	930	905
E	IS	445 (75)	605 (82)	875 (98)	930 (100)	1010 (112)
Avg Type I		555	700	835	885	920
Avg Type IS		485 (87)	660 (94)	905 (108)	955 (108)	1020 (111)
(b) 5½ Gal Per Bag						
A	I	495	605	730	760	775
A	IS	420 (85)	610 (101)	880 (121)	920 (121)	925 (119)
B	I	380	570	740	790	810
B	IS	395 (104)	520 (91)	750 (101)	885 (112)	935 (115)
C	I	410	550	630	695	690
C	IS	365 (89)	550 (100)	730 (116)	815 (117)	815 (118)
D	I	500	610	750	780	810
D	IS	400 (80)	525 (86)	775 (103)	925 (119)	935 (115)
E	I	495	670	805	855	790
E	IS	375 (76)	505 (75)	790 (98)	915 (107)	895 (113)
Avg all Type I		455	600	730	775	775
Avg all Type IS		390 (86)	540 (90)	785 (108)	890 (115)	900 (116)
(c) 6½ Gal Per Bag						
A	I	420	560	635	695	655
A	IS	365 (87)	535 (96)	715 (113)	800 (115)	820 (125)
B	I	330	485	695	760	720
B	IS	305 (92)	440 (91)	690 (99)	800 (105)	825 (114)
C	I	345	505	565	600	615
C	IS	315 (91)	475 (94)	690 (122)	775 (129)	755 (123)
D	I	435	555	640	720	690
D	IS	345 (79)	485 (87)	730 (114)	835 (116)	870 (126)
E	I	440	620	730	745	700
E	IS	310 (70)	445 (72)	610 (84)	780 (105)	850 (121)
Avg all Type I		395	545	655	705	675
Avg all Type IS		330 (84)	475 (87)	685 (105)	800 (113)	825 (122)
(d) 7½ Gal Per Bag						
A	I	315	425	590	605	580
A	IS	270 (86)	435 (102)	660 (112)	730 (121)	770 (133)
B	I	240	370	520	645	610
B	IS	235 (98)	365 (99)	640 (123)	780 (121)	815 (134)
C	I	270	430	530	530	540
C	IS	220 (81)	355 (83)	555 (105)	630 (119)	650 (120)
D	I	335	455	600	625	645
D	IS	275 (82)	395 (87)	630 (105)	760 (122)	750 (116)
E	I	355	490	670	635	615
E	IS	225 (63)	340 (69)	540 (81)	650 (102)	745 (121)
Avg all Type I		305	435	580	610	600
Avg all Type IS		245 (80)	380 (87)	605 (104)	710 (116)	745 (124)

[a] Specimens were 6- by 6- by 21-in. beams tested in accordance with ASTM Method C–78 with third-point loading on an 18-in. span-side as molded in tension. Specimens stored in moist air until tested. Each value is an average of 5 tests. Figures in parentheses represent ratio of the strength of Type IS to corresponding Type I, in percent.

The fourth group was moist cured 1 day, followed by 88 days in laboratory air and then immersed in water 1 day. The fifth group was moist cured for 7 days, followed by 82 days in laboratory air and then immersed in water 1 day.

The results of the compressive

strength tests on these specimens and continuously moist-cured specimens are given in Table 6. The ratios of the compressive strengths of the intermittently-cured specimens to the strengths of similar continuously moist-cured specimens are also given.

The first group of 28-day specimens moist cured 1 day and then tested dry showed an average reduction in strength of 30 percent for the portland cement concrete and 31 percent for the slag cement concrete when compared with the compressive strengths of similar moist-cured specimens. The second group showed a loss in strength of 36 percent for the portland cement concrete and 41 percent for the slag cement concrete.

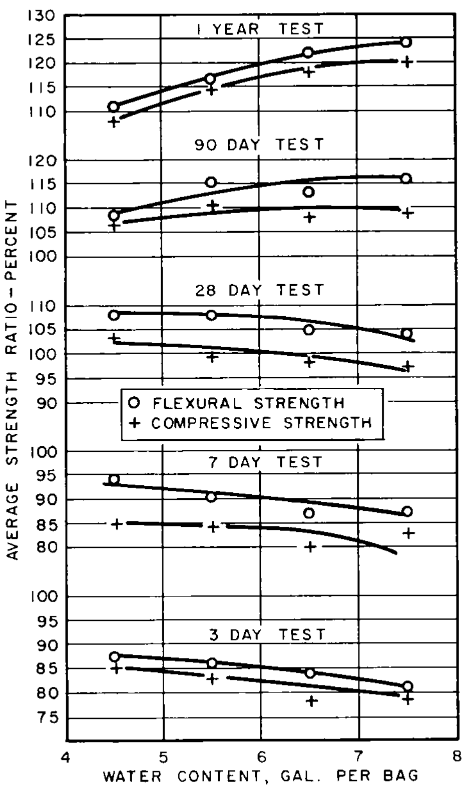

Figure 2. Relative effect of water content on ratio of strength of slag cement concrete to strength of portland cement concrete.

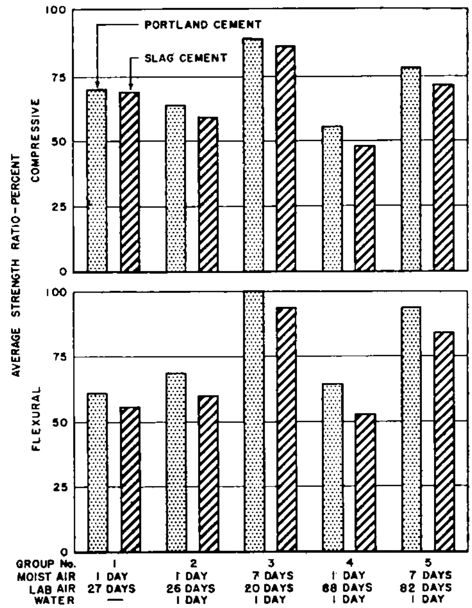

Figure 3. Strength of intermittently-cured concrete expressed as a ratio of strength of concrete given continuous moist curing.

The third group showed losses of 10 and 13 percent, respectively. The 28-day specimens prepared with portland cements which were intermittently cured showed a smaller average reduction in compressive strength than similarly cured specimens prepared with slag cements. However, this difference was very slight. The specimens in group 1 which were moist cured for 1 day only and then tested dry gave higher strength for both the portland and the slag cement concretes than the specimens in group 2 which were moist cured 1 day and immersed in water 1 day immediately prior to testing.

The specimens in the fourth group which were tested at 90 days showed an average reduction in strength of 44 percent for the portland cement concrete and 52 percent for the slag cement concrete. The fifth group showed losses of 22 and 28 percent, respectively. The 90-day intermittently-cured specimens prepared with portland cement from all five sources showed less reduction in strength than the corresponding specimens prepared with slag cement. The percentage reduction in compressive strength for the slag cement specimens tested at 90 days was greater than the similarly cured slag cement specimens tested at 28 days. The actual compressive strengths of the intermittently-cured specimens for the portland cement concretes and the slag cement concretes which were moist cured the same length of time, were approximately the same for those tested at 28 days as for those tested at 90 days. This appears to indicate that the dry curing was not beneficial in development of strength.

Results of tests for flexural strength of intermittently-cured specimens are given in Table 7. These data show the same general trends as were shown for compressive strength. The portland cement concretes show less reduction in flexural strength due to intermittent curing than the corresponding slag cement concretes. This difference between the reductions shown for the portland cement and the slag cement concretes is greater for the flexural strength tests than for the compressive strength tests. Concrete prepared with four of the five portland cements and one of the slag cements and tested at 28 days developed as much or more strength when given only 7 days initial moist curing and immersed in water 24 hours prior to tesing as the concrete moist cured continuously for 28 days. The 90-day tests did not show this feature. The results of these tests, summarized in Figure 3, indicate that concrete prepared with slag cement may be more susceptible to defective curing practices than concrete prepared with portland cement. It is, of course, desirable to cure all concrete as perfectly as possible. More care must be exercised for slag cement concrete to insure the obtainment of the de-

TABLE 6

COMPRESSIVE STRENGTH (PSI) TESTS ON SPECIMENS CURED INTERMITTENTLY [a]

Cement		5½ Gal per Bag						
Source	Type	1 Day Moist 27 Days Dry [b]	1 Day Moist 26 Days Dry 1 Day Soak [b]	7 Days Moist 20 Days Dry 1 Day Soak [b]	28 Days Moist [c]	1 Day Moist 88 Days Dry 1 Day Soak [b]	7 Days Moist 82 Days Dry 1 Day Soak [b]	90 Days Moist [c,d]
A	I	4420 (77)	3980 (69)	5100 (88)	5770	4000 (62)	5140 (80)	6440
	IS	4080 (69)	3760 (63)	5360 (90)	5940	3620 (51)	5450 (76)	7140
B	I	3420 (63)	3050 (56)	4660 (86)	5400	3190 (50)	4850 (76)	6380
	IS	4000 (67)	3270 (55)	4790 (81)	5950	3690 (48)	4950 (65)	7640
C	I	3320 (64)	3030 (59)	4720 (91)	5160	2970 (54)	4490 (82)	5500
	IS	3180 (61)	2840 (55)	4490 (86)	5200	2840 (44)	4620 (72)	6390
D	I	4140 (72)	3620 (62)	5260 (91)	5790	3810 (55)	5160 (75)	6920
	IS	4050 (69)	3450 (59)	5010 (86)	5830	3520 (46)	5270 (69)	7600
E	I	4040 (75)	3820 (70)	4960 (92)	5420	3850 (62)	4990 (80)	6240
	IS	3700 (80)	2870 (62)	4180 (91)	4600	2990 (51)	4660 (79)	5900
Avg all Type I		3870 (70)	3500 (64)	4940 (90)	5510	3560 (56)	4930 (78)	6300
Avg all Type IS		3800 (69)	3240 (59)	4770 (87)	5500	3330 (48)	4990 (72)	6930

[a] Specimens were 6- by 12-in. cylinders. Each value is an average of five tests. Figures in parentheses represent the ratio of the strength of the intermittently cured specimens to the strength of the 28-day moist cured specimens, in percent.
[b] Specimens capped with sulfur cement.
[c] Specimens capped with neat Lumnite cement.
[d] These spec mens made on different day from the other 90-day specimens cured intermittently; same values as given in Table 4.

TABLE 7

FLEXURAL STRENGTH (PSI) TESTS ON SPECIMENS CURED INTERMITTENTLY [a]

Cement		5½ Gal Per Bag						
Source	Type	1 Day Moist 27 Days Dry	1 Day Moist 26 Days Dry 1 Day Soak	7 Days Moist 20 Days Dry 1 Day Soak	28 Days Moist	1 Day Moist 88 Days Dry 1 Day Soak	7 Days Moist 82 Days Dry 1 Day Soak	90 Days Moist [b]
A	I	435 (58)	565 (76)	715 (96)	745	600 (79)	710 (93)	760
	IS	470 (54)	585 (67)	730 (83)	875	535 (58)	720 (78)	920
B	I	445 (63)	425 (60)	750 (106)	710	445 (56)	785 (99)	790
	IS	470 (63)	515 (69)	785 (105)	745	525 (59)	745 (84)	885
C	I	445 (63)	420 (59)	710 (100)	710	370 (53)	635 (91)	695
	IS	395 (51)	410 (53)	730 (95)	770	355 (44)	720 (88)	815
D	I	485 (64)	570 (75)	765 (101)	760	575 (74)	780 (100)	780
	IS	490 (59)	465 (56)	815 (99)	825	485 (52)	830 (90)	925
E	I	480 (63)	570 (75)	785 (103)	765	540 (63)	750 (88)	855
	IS	435 (55)	465 (59)	720 (91)	790	445 (49)	725 (79)	915
Avg all Type I		460 (62)	510 (69)	745 (101)	740	505 (65)	730 (94)	775
Avg all Type IS		450 (56)	490 (61)	755 (94)	800	470 (53)	750 (84)	890

[a] Specimens were 6- by 6- by 21-in. beams tested in accordance with ASTM Method C 78 with third-point loading on an 18-in. span-side as molded in tension. Each value is an average of five tests. Figures in parentheses represent the ratio of the strength of the intermittently-cured specimens to the strength of the 28-day moist-cured specimens, in percent.

[b] These specimens made on different day from the other 90-day specimens cured intermittently; same values as given in Table 5.

sirable features furnished by this type of cement.

Sonic and Static Moduli of Elasticity

Results of tests for sonic modulus of elasticity are given in Table 8. Determinations were made on the 6- by 6- by 21-in. beams prior to tests for flexural strength. In general, the the compressive strength tests were shown. At ages of 3, 7, and 28 days the portland cement concrete had higher average sonic moduli and at 90 days and 1 year the slag cement same trends as were obtained with concrete had higher average sonic moduli. The difference in moduli for the two types of cement is not great, usually less than 5 percent.

Data for the static modulus of elasticity are given in Table 9. These data are limited to tests at each age for the 4½ gal mix and to tests at one year for the other mixes. Determinations were made on 6- by 12-in. cylinders by use of an autographic stress-strain recorder with a 6-in. gage length prior to tests for compressive strengths. The same trends were shown for the static moduli as were shown for the sonic moduli. The sonic moduli were about 7 percent higher than the static moduli.

Drying Shrinkage

Tests for shrinkage on drying were made on concrete specimens prepared with each of the portland and slag cements and containing 5½ and 6½ gal of water per sack of cement. The specimens were 3- by 4- by 16-in. beams with gage studs cast in each end. Three beams prepared with each cement and water content were moist cured for 2 days and three were moist cured for 7 days prior to the beginning of the measurements for shrinkage. The specimens were stored in room air at 73 F and 50 percent relative humidity for 90 days, and length measurements were made

TABLE 8
SONIC MODULUS OF ELASTICITY [a]

Cement		Modulus of Elasticity (psi × 10^6)					
Source	Type	3 Days	7 Days	28 Days	90 Days	180 Days	1 Year
(a) 4½ Gal Per Bag							
A	I	5.44	6.01	6.64	6.78	7.07	7.25
A	IS	5.22	5.38	6.19	6.75	7.01	7.10
B	I	4.99	5.70	6.51	6.83	6.95	7.05
B	IS	5.03	5.52	6.43	6.95	7.13	7.21
C	I	5.28	6.40	6.56	6.57	6.82	6.93
C	IS	5.01	6.25	6.39	6.51	6.94	6.99
D	I	5.22	6.05	6.60	6.86	7.25	7.01
D	IS	4.97	5.68	6.54	6.85	7.00	7.02
E	I	5.58	6.12	6.71	6.90	6.94	6.96
E	IS	4.95	5.38	6.15	6.50	6.76	6.96
Avg all Type I		5.30	6.06	6.60	6.79	7.01	7.04
Avg all Type IS		5.04	5.64	6.34	6.71	6.97	7.06
(b) 5½ Gal Per Bag							
A	I	—	—	6.38	6.76	6.82	6.92
A	IS	—	—	6.17	6.70	6.84	6.91
B	I	—	5.70	6.46	6.52	6.62	6.69
B	IS	—	4.95	6.11	6.72	6.91	7.09
C	I	—	5.75	6.33	6.55	6.69	6.78
C	IS	—	5.65	6.39	6.57	6.67	6.80
D	I	—	6.08	6.43	6.69	6.75	6.82
D	IS	—	5.95	6.65	7.01	7.18	7.28
E	I	—	6.20	6.65	6.78	6.95	7.07
E	IS	—	5.57	6.27	6.54	6.91	7.19
Avg all Type I		—	5.93	6.45	6.65	6.77	6.86
Avg all Type IS		—	5.53	6.32	6.71	6.90	7.05
(c) 6½ Gal Per Bag							
A	I	4.95	5.73	6.32	6.66	6.80	6.68
A	IS	4.79	5.45	6.04	6.71	6.92	6.87
B	I	4.44	5.44	6.19	6.57	6.70	6.60
B	IS	4.26	4.97	5.86	6.41	6.71	6.78
C	I	4.62	5.57	6.15	6.33	6.46	6.52
C	IS	4.38	5.42	6.20	6.57	6.76	6.72
D	I	4.91	5.69	6.27	6.59	6.72	6.61
D	IS	4.66	5.35	6.22	6.63	6.89	6.80
E	I	5.06	5.84	6.45	6.69	6.77	6.66
E	IS	4.58	5.30	5.97	6.59	6.81	6.84
Avg all Type I		4.80	5.65	6.28	6.57	6.69	6.61
Avg all Type IS		4.53	5.30	6.06	6.58	6.82	6.80
(d) 7½ Gal Per Bag							
A	I	4.18	5.22	5.80	6.07	—	6.18
A	IS	3.85	4.86	5.72	6.16	—	6.66
B	I	3.66	4.84	5.62	6.00	—	6.13
B	IS	3.59	4.61	5.51	6.27	—	6.54
C	I	3.99	5.06	5.83	5.98	—	6.02
C	IS	3.65	4.72	5.73	6.20	—	6.40
D	I	4.36	5.19	5.89	6.04	—	6.15
D	IS	4.00	4.76	5.82	6.33	—	6.42
E	I	4.56	5.51	6.15	6.19	—	6.23
E	IS	3.94	4.73	5.67	6.11	—	5.42
Avg all Type I		4.15	5.16	5.86	6.06	—	6.14
Avg all Type IS		3.81	4.74	5.69	6.21	—	6.49

[a] Sonic modulus determined on 6- by 6- by 21-in. beams prior to testing for flexural strength. Specimens continuously moist cured. Each value is average of five tests.

TABLE 9

STATIC MODULUS OF ELASTICITY [a]

Cement		Modulus of Elasticity (psi × 10^6)				
Source	Type	3 Days	7 Days	28 Days	90 Days	1 Year
		(a) 4½ Gal Per Bag				
A	I	4.82	5.89	6.24	6.69	6.66
A	IS	4.63	5.70	6.28	6.86	6.85
B	I	4.53	5.70	6.01	6.65	6.83
B	IS	4.11	5.67	6.63	7.14	6.96
C	I	4.30	5.52	5.92	6.51	6.68
C	IS	4.31	5.61	5.95	6.59	6.76
D	I	4.81	5.91	6.26	6.20	6.65
D	IS	4.38	4.88	7.30	6.93	6.96
E	I	4.90	6.31	6.82	6.39	6.74
E	IS	4.81	5.29	6.06	6.34	6.84
Avg all Type I		4.67	5.87	6.25	6.49	6.71
Avg all Type IS		4.45	5.43	6.44	6.77	6.87
		(b) 5½ Gal Per Bag				
A	I	—	—	—	—	6.74
A	IS	—	—	—	—	6.65
B	I	—	—	—	—	6.42
B	IS	—	—	—	—	6.62
C	I	—	—	—	—	6.42
C	IS	—	—	—	—	6.34
D	I	—	—	—	—	6.43
D	IS	—	—	—	—	7.12
E	I	—	—	—	—	6.90
E	IS	—	—	—	—	6.60
Avg all Type I		—	—	—	—	6.58
Avg all Type IS		—	—	—	—	6.67
		(c) 6½ Gal Per Bag				
A	I	—	—	—	—	6.26
A	IS	—	—	—	—	6.68
B	I	—	—	—	—	6.48
B	IS	—	—	—	—	6.92
C	I	—	—	—	—	6.21
C	IS	—	—	—	—	6.73
D	I	—	—	—	—	6.54
D	IS	—	—	—	—	6.70
E	I	—	—	—	—	6.69
E	IS	—	—	—	—	6.99
Avg all Type I		—	—	—	—	6.44
Avg all Type IS		—	—	—	—	6.80
		(d) 7½ Gal Per Bag				
A	I	—	—	—	—	5.70
A	IS	—	—	—	—	6.60
B	I	—	—	—	—	5.69
B	IS	—	—	—	—	6.70
C	I	—	—	—	—	5.74
C	IS	—	—	—	—	6.19
D	I	—	—	—	—	6.26
D	IS	—	—	—	—	6.77
E	I	—	—	—	—	5.56
E	IS	—	—	—	—	6.45
Avg all Type I		—	—	—	—	5.79
Avg all Type IS		—	—	—	—	6.54

[a] Determined on 6- by 12-in. cylinders prior to testing for compressive strength. Specimens were continuously moist cured. Each value is average of five tests.

frequently. The specimens were then immersed in water at 73 F for 15 days. This procedure was repeated three times.

The average results of the shrinkage tests for concretes prepared with the two types of cement and 5½ and 6½ gal of water per sack of cement are shown in Figure 4 and for the shrinkage at the end of the third drying period are given in Table 10. These are averages for all concretes prepared with each type of cement. The differences between the concrete specimens prepared with the two types of cement are too small to be significant. It appears that concern over the shrinkage of concrete prepared with slag cement is unfounded. The results of the drying shrinkage tests of mortar bars by ASTM Method C 340-55 T (Table 1) indicate the same conclusions.

Freezing-and-Thawing Tests

Freezing-and-thawing tests were made on concretes prepared with 5½ and 6½ gal of water per bag of cement. Beams measuring 3 by 4 by 16 in. were moist cured for 7 days, followed by 14 days of storage in laboratory air and immersion in water water for 7 days prior to freezing. Freezing and thawing was in accord-

TABLE 10
DRYING SHRINKAGE OF CONCRETE

Water Content (gal/bag)	Initial Moist Curing (days)	Final Shrinkage[1] (%)	
		Portland Cement Concrete	Slag Cement Concrete
5½	2	0.040	0.041
5½	7	0.038	0.040
6½	2	0.042	0.037
6½	7	0.040	0.039

[1] Shrinkage after 2 cycles of drying for 60 days then 41 days immersion in water followed by an additional 60 days drying.

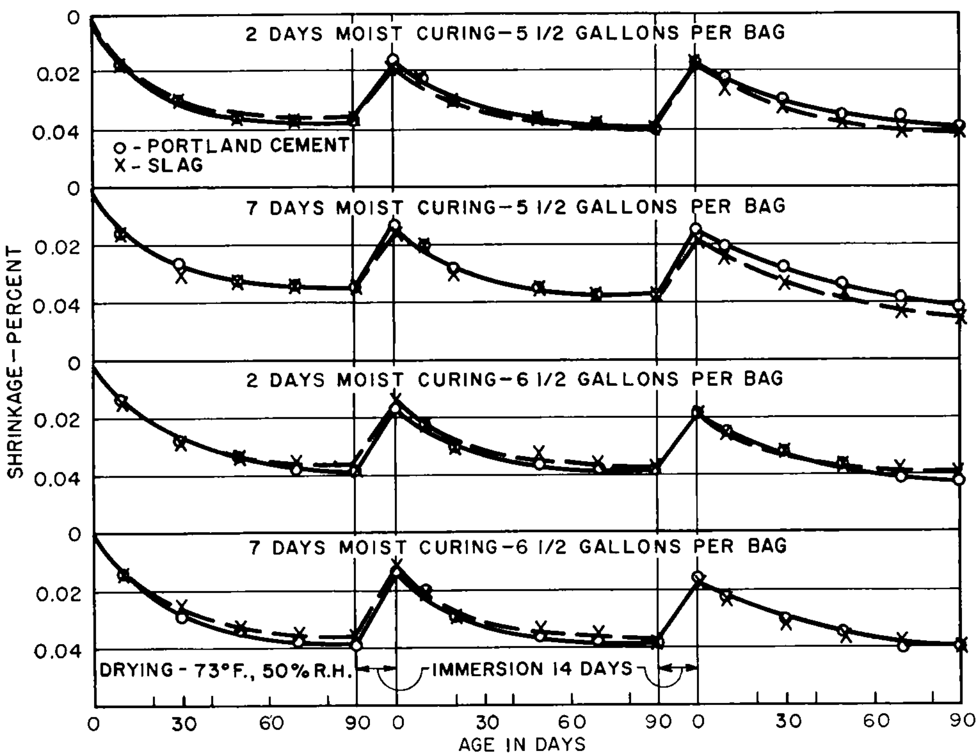

Figure 4. Effect of portland blast-furnace slag cement on drying shrinkage.

dance with ASTM Method C 292 for slow freezing and thawing in water. Results of these tests and the durability factors of the concretes are given in Table 11 and Figure 5. The durability factor was calculated from

$$DF = \frac{P\,N}{M}$$

in which

DF = durability factor;
P = relative dynamic modulus of elasticity at N cycles, percent (60 percent minimum);
N = number of cycles at which P reached 60 percent or 300, whichever is less; and
M = 300 (cycles).

These test shows that the concretes prepared with the slag cement from all five sources had better durability as determined by laboratory freezing and thawing than the corresponding concretes prepared with the portland cements.

Scaling Tests Using Calcium Chloride for Ice Removal

Concrete slabs 16 by 24 by 4 in. deep were prepared with each cement for outdoor exposure tests. They were moist cured for 28 days and then stored in the outdoor exposure area. A dam was cast around the top perimeter of each specimen and when freezing was expected the top surface of each specimen was covered with ¼ to ½ in. of water. The slabs were in the exposure area about 6 months before freezing occurred. Each morning after the water had frozen, flake calcium chloride was spread over the ice at a rate of 2.4 lb per square yard of ice-encrusted surface. After the ice had thawed (usually about 3 hr later) the calcium chloride solution was washed off and fresh water was left on the surface. The slabs were examined

TABLE 11
RESULTS OF FREEZING-AND-THAWING TESTS [a]

Cement		% of Original N^2 After Freezing and Thawing																	
Source	Type	10 Cycles	20 Cycles	50 Cycles	100 Cycles	150 Cycles	200 Cycles	250 Cycles	300 Cycles	D.F.	10 Cycles	20 Cycles	30 Cycles	100 Cycles	150 Cycles	200 Cycles	250 Cycles	300 Cycles	D.F.[b]
		5½ Gal Per Bag									6½ Gal Per Bag								
A	I	94	101	100	99	92	86	81	67	67	99	100	96	92	88	75	64	—	53
A	IS	99	104	102	106	105	102	95	86	86	101	102	101	104	102	90	81	75	75
B	I	97	104	99	100	93	87	81	67	67	100	100	96	93	86	67	61	—	51
B	IS	99	105	103	106	106	105	99	89	89	101	104	103	103	99	82	64	60	60
C	I	99	106	96	94	81	72	61	—	51	100	101	96	91	87	72	53	—	46
C	IS	101	105	103	102	102	99	96	86	86	100	102	101	98	94	79	73	66	66
D	I	100	104	102	98	94	87	81	70	70	101	103	96	94	92	82	64	—	53
D	IS	101	104	103	103	104	102	98	92	92	98	98	100	98	95	83	74	66	66
E	I	102	104	101	102	94	86	79	65	65	99	100	96	93	92	74	60	—	50
E	IS	98	102	101	105	104	100	94	88	88	101	102	100	98	92	78	69	63	63
Avg all Type I										64									51
Avg all Type IS										88									66

[a] Specimens were 3- by 4- by 16-in. beams frozen and thawed in accordance with ASTM Method C-292 for slow freezing and thawing in water. Each value is an average of tests on 5 beams.
[b] Durability factor.

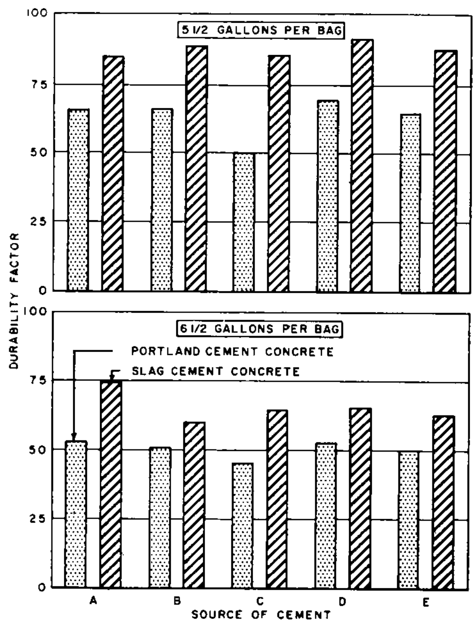

Figure 5. Results of freezing-and-thawing tests on concrete prepared with portland or slag cements.

periodically and rated according to the amount and depth of scaling of the exposed surface. The ratings were based on visual observations. A rating of 0 indicated that no scaling had occurred and a rating of 10 indicated deep scaling over the entire specimen.

The slab ratings are give in Table 12. Three mixes were used, containing 5½, 6½ and 7½ gal of water per bag of cement. The tests were continued through two winters with a total of 55 cycles of freezing and thawing. These tests show very little difference in behavior of the portland cement concrete and the slag cement concrete. However, considerable differences were found between the cements, both portland and slag, prepared by the different mills, and used in concretes containing 5½ gal of water per bag of cement. The concrete specimens prepared with cements, both portland and slag, from sources A and B were generally much more resistant to scaling by the de-icing agent than were the other concretes. When a water content of 6½ or 7½ gal per bag was used, severe scaling was found on all specimens. It is apparent that in connection with the scaling of concrete caused by de-icing agents, the water content of the concrete is of primary importance. Only when the water content is kept at a low value will differences in the quality of the con-

TABLE 12
RESISTANCE OF CONCRETE TO SCALING [a]

Cement		Rating After Freezing and Thawing with $CaCl_2$ [b]								
		5½ Gal Per Bag			6½ Gal Per Bag			7½ Gal Per Bag		
Source	Type	20 cycles	35 cycles	55 cycles	20 cycles	35 cycles	55 cycles	20 cycles	35 cycles	55 cycles
A	I	0	0	1	4	7	9	7	8	10
A	IS	0	1	1	4	7	9	4	9	6
B	I	1	2	2	4	7	9	6	8	9
B	IS	1	2	2	4	9	9	6	9	10
C	I	2	3	8	4	6	6	8	9	10
C	IS	2	6	7	6	9	9	6	9	10
D	I	1	2	4	8	9	10	9	9	10
D	IS	4	6	7	7	9	10	8	9	10
E	I	2	5	8	2	8	9	8	9	10
E	IS	4	6	7	6	9	9	9	9	10

[a] Specimens were 16- by 20- by 4-in. slabs, stored in moist air 28 days prior to placing in exposure area. Air content approximately 5½ percent. Each value is an average of two tests.

[b] Rating of 0 indicates no scaling, 10 indicates deep scaling over entire surface.

crete caused by other factors influence the results obtained.

Mortar Bar Expansion Tests

The alkali-reactivity of both the portland and portland blast-furnace slag cements was evaluated by the mortar bar tests specified in Federal Specification SS-C-208b and ASTM Specification C 340-55 (tests made in accordance with ASTM Method C 227-52 T) for portland-pozzolan cement. These tests involve the determination of the expansion of 1- by 1- by 10-in. mortar specimens prepared with crushed and graded Pyrex glass. The principal difference between these two tests is the use of a significantly higher water-cement ratio in the ASTM procedure. In addition, a modified mortar bar test was made using the same size of specimen prepared from a 1:2 mortar containing ASTM C 109 Ottawa sand with various amounts of No. 8 to 30 size reactive opal and having a water-cement ratio of 0.50 by weight. The specimens for each test were stored in moist air at 100 F.

The expansion data for all mortar bar tests are given in Table 13. Both Federal Specification SS-C-208b and ASTM Specification C 340-55 limit the expansion of mortar bars to not more than 0.02 percent at 14 days or 0.06 percent at 8 weeks. Presumably a cement which meets these limits would not be expected to cause excessive expansion in concrete containing alkali-reactive aggregates. The type I portland cements from sources A, C and E would be considered as potentially expansive by the ASTM procedure, but only the type I cements from sources C and E would be similarly classified by the Federal procedure. None of the type IS cements would be considered as potentially reactive by either procedure based on the expansions at 8 weeks.

The modified mortar bar test in which opal was used as the reactive material is similar to tests used by numerous investigators to study the various factors which influence the expansion resulting from the alkali-aggregate reaction. Because of differences in reactivity of opal and other naturally occurring materials obtained from different sources, expansion tests using natural aggregates have never been standardized to the point of establishing a definite criterion by which the reactivity of a cement can be judged. Comparison of the expansions given in Table 13 for mortar bars prepared with and without opal indicate that any expansion of more than 0.04 percent can be attributed to a reaction between the alkalies of the cement and the opal. Perhaps the nearest approach to an applicable criterion for an excessive amount of expansion in this test is found in the Specification for Concrete Aggregates, ASTM C 33-57, where an expansion of more than 0.10 percent at 6 months is used to define potentially reactive aggregates. Using this criterion, it is found that there is a pessimum amount of opal which will cause an excessive expansion at 6 months with the type I portland cements from sources A, C, and E and the type IS slag cements from sources C and E. For the cements from sources A, B, D and E the expansion of the slag cements are less than those for the portland cements, but the slag cement from source C shows a greater expansion than the portland cement from that source. It should be noted that for this source, the alkali content of the type IS slag cement is nearly double that of the type I cement, thus accounting for the increase in expansion. Apparently, the alkalies present in blast-furnace slag are available for reaction with susceptible aggregates.

The results of the modified mortar bar tests using opal appear to be

TABLE 13
RESULTS OF MORTAR BAR EXPANSION TEST [a]

Cement				Expansion of 1- by 1- by 10-Inch Mortar Bars (%)							
				ASTM Method C 227–52 T				Federal SS–C–208B			
Source	Type	Slag (%)	Alkali [b] (%)	2 Wk.	8 Wk.	6 Mo.	1 Yr.	2 Wk.	8 Wk.	6 Mo.	1 Yr.
A	I	—	0.32	0.05	0.12	0.19	0.20	0.02	0.02	0.05	0.03
A	IS	45	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
B	I	—	0.19	0.01	0.02	0.14	0.16	0.00	0.03	0.07	0.10
B	IS	45	0.22	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
C	I	—	0.32	0.01	0.14	0.23	0.24	0.01	0.10	0.10	0.14
C	IS	25	0.61	0.00	0.02	0.07	0.11	0.00	0.00	0.01	0.02
D	I	—	0.21	0.00	0.00	0.05	0.10	0.00	0.01	0.02	0.03
D	IS	40	0.22	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
E	I	—	0.82	0.17	0.20	0.26	0.22	0.14	0.16	0.13	0.16
E	IS	35	0.75	0.03	0.05	0.06	0.07	0.03	0.04	0.04	0.04
				Modified Test, 0% Opal				Modified Test, 0.5% Opal			
A	I	—	0.32	0.02	0.02	0.02	0.02	0.02	0.12	0.28	0.35
A	IS	45	0.37	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.03
B	I	—	0.19	0.02	0.03	0.03	0.04	0.01	0.02	0.06	0.12
B	IS	45	0.22	0.00	0.02	0.02	0.02	0.01	0.02	0.03	0.03
C	I	—	0.32	0.01	0.01	0.02	0.02	0.02	0.05	0.11	0.18
C	IS	25	0.61	0.00	0.00	0.01	0.02	0.01	0.18	0.27	0.27
D	I	—	0.21	0.00	0.01	0.01	0.02	0.00	0.01	0.02	0.07
D	IS	40	0.22	0.00	0.02	0.01	0.01	0.00	0.02	0.01	0.02
E	I	—	0.82	0.01	0.02	0.02	0.02	0.07	0.12	0.14	0.14
E	IS	35	0.75	0.00	0.01	0.01	0.02	0.01	0.08	0.11	0.11
				Modified Test, 1.0% Opal				Modified Test, 2.0% Opal			
A	I	—	0.32	0.02	0.17	0.33	0.56	0.02	0.07	0.10	0.13
A	IS	45	0.37	0.00	0.03	0.08	0.12	0.00	0.04	0.04	0.07
B	I	—	0.19	0.01	0.03	0.06	0.06	0.01	0.02	0.03	0.04
B	IS	45	0.22	0.00	0.01	0.02	0.03	0.01	0.02	0.02	0.03
C	I	—	0.32	0.01	0.07	0.16	0.35	0.00	0.04	0.08	0.10
C	IS	25	0.61	0.02	0.24	0.40	0.45	0.03	0.16	0.24	0.32
D	I	—	0.21	0.00	0.00	0.01	0.02	0.00	0.01	0.01	0.02
D	IS	40	0.22	0.01	0.02	0.01	0.01	0.00	0.01	0.01	0.01
E	I	—	0.82	0.16	0.26	0.29	0.30	0.20	0.38	0.55	0.57
E	IS	35	0.75	0.03	0.14	0.26	0.28	0.04	0.10	0.20	0.26

[a] Each value is average of tests on 4 or 6 beams.
[b] Equivalent alkalies as Na_2O (see Table 1).

somewhat in conflict with the results obtained with the ASTM and Federal procedures for determining reactivity. The modified tests indicate that the slag constituent of the high-alkali portland blast-furnace slag cements is not entirely effective in preventing expansion resulting from the alkali-aggregate reaction under the conditions of this test.

It was noted (Table 1) that two of the slag cements had an equivalent alkali content of more than 0.6 percent, which would cause them to be classified as high-alkali cements. It was also noted that in the modified method of test when 1 percent of opal was used, mortar prepared with the slag cement with the greatest amount of alkali did not develop the most expansion at an age of one year. Apparently, some component of the cement had a modifying influence on the amount of expansion. It was believed that this might have been the amount of slag in the slag cement. Upon request to the manufacturers of these cements, it was found that the cements from sources A and B contained 45 percent slag, that from source C had 25 percent, that from source D had 40 percent, and that from source E had 35 percent.

Figure 6, showing the relation between the amount of expansion of mortar containing 1 percent opal and tested at an age of 1 year, and a value obtained by dividing the slag

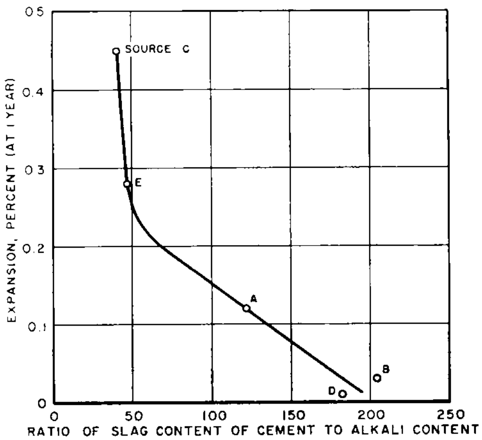

Figure 6. Effect of slag content and alkali content of slag cements on expansion of mortar containing 1 percent alkali-reactive opal.

content of each cement by the equivalent alkali content expressed as sodium oxide, indicates that the expansion decreases as the ratio of the slag content of the cement increases. It also shows that for equivalent alkali content of 0.6 percent, for example, it would be highly desirable to have a slag content of the cement appreciably higher than 30 percent to prevent the alkali-aggregate reaction.

CONCLUSIONS

The conclusions obtained from the results of this series of tests support those given in the preliminary report. The conclusions of the preliminary report are combined with those of this final report.

Concrete specimens prepared with the portland blast-furnace slag cements and continuously moist-cured had lower early strengths than those prepared with portland cement. However, at ages of 90 days and 1 year the slag cement concretes had higher strengths, and although no tests at ages greater than one year were made, the ultimate strength of the slag cement concretes most likely will continue to exceed those of the concretes prepared with portland cement.

Both compressive and flexure tests showed the same trends with respect to type of cement.

Concretes prepared with both types of cement and subjected to intermittent curing that included one or seven days of initial moist curing in most cases had less strength than duplicate concretes which were continuously moist cured. The concretes prepared with slag cement were affected more by this partial curing than those prepared with portland cement. This is taken to indicate that slag cement concrete may require more care and longer initial moist curing than portland cement concrete.

At an age of one year, although the strengths of both types of concretes decreased with increasing amounts of water, the strengths of the concrete prepared with slag cement appeared to be affected less by changes in the water-cement ratio than the strengths of concretes prepared with portland cement. This indicates that, provided it is given adequate curing, concrete prepared with slag cement will tolerate greater variations in the amount of mixing water used and still give more uniform strength than portland cement concrete.

Concretes prepared with slag and portland cements from the same source had practically the same amount of shrinkage on drying.

The sonic and static moduli of elasticity of slag cement concrete were slightly lower at early ages and higher at later ages than those for portland cement concrete.

The amount of air-entraining agent needed to entrain 5½ percent of air in concrete was not uniform for the slag cements from the different sources. This varied from the same amount as was used with the corresponding portland cements to about 2½ times that quantity.

Concretes prepared with the slag cements for both the $5\frac{1}{2}$- and $6\frac{1}{2}$-gal mixes had greater durability, as measured by laboratory freezing-and-thawing tests, than comparable portland cement concretes.

There was no appreciable difference in the resistance to scaling between the concretes prepared with slag cements and the corresponding portland cements in outdoor tests where $CaCl_2$ was used for de-icing.

Mortars prepared with slag cements usually produced less expansion when used with reactive aggregates than similar mortars prepared with the corresponding portland cements. The amount of slag used in the manufacture of the type IS cement is beneficial in controlling alkali-aggregate reaction. The best results are obtained with a low-alkali cement containing a high percentage of slag. Portland blast-furnace slag cement with a sufficiently high slag content may be suitable for use with highly alkali-reactive aggregate.

REFERENCES

1. Grieb, W. E., and Werner, G., "Tests of Concrete Containing Portland Blast-Furnace Slag Cement." *HRB Proc.*, 40:253 (1957).
2. Grieb, W. E., and Werner, G., "Tests of Concrete Containing Portland Blast-Furnace Slag Cement." *Public Roads*, 29: 10, 227 (Oct. 1957).