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Final Report of Tests of Concrete Containing Portland Blast-Furnace Slag Cement

BY THE DIVISION OF PHYSICAL RESEARCH
BUREAU OF PUBLIC ROADS

Reported[1] by William E. Grieb and George Werner, Highway Research Engineers

Because portland blast-furnace slag cement is being used increasingly as an alternate for ordinary portland cement, the Bureau of Public Roads several years ago undertook a laboratory study of the strength, durability and other properties of air-entrained concretes prepared with portland blast-furnace slag cement as compared with concrete made with ordinary portland cement. The final results of that study are reported in this article.

The comparisons showed that slag cement concrete had lower early strength but higher ultimate strength than comparable portland cement concrete, according to both compressive and flexural strength tests. Slag cement concrete also had greater durability, under laboratory freezing and thawing tests. There was little difference between the two types in resistance to scaling, in outdoor tests where calcium chloride was used for de-icing.

Tests under intermittent curing conditions indicated that the slag cement concrete may require more care and longer initial moist curing; but given adequate curing, the slag cement concrete tolerated greater variations in the amount of mixing water used. Slag cement with sufficiently high slag content may be suitable for use with highly alkali-reactive aggregate, since the slag content is beneficial in controlling the alkali-aggregate reaction.

Introduction

A PRELIMINARY REPORT on tests of concrete containing portland blast-furnace slag cement, conducted by the Bureau of Public Roads, was published in 1957.[2] Tests were made of the physical properties of air-entrained concretes prepared with five type I portland cements and five type IS portland blast-furnace slag cements, obtained from five different cement plants. At each plant, the same clinker was used in the manufacture of both the portland cement and the portland blast-furnace slag cement furnished for the tests. By way of definition, portland blast-furnace slag cement is an intimately interground mixture of portland cement clinker and granulated blast-furnace slag.

The preliminary report presented the results of all tests that had been completed at that time, including results of tests of compressive and flexural strengths and sonic moduli of elasticity at ages ranging from 3 through 90 days, on moist-cured concrete prepared with 5½, 6½, and 7½ gallons 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 also reported.

All tests which were still in progress at the time of the preliminary report have now been completed. Strength tests have been made through ages of 1 year for moist-cured specimens and through 90 days for intermittently cured specimens. Freezing and thawing tests were continued through 300 cycles. Volume change measurements were made through a period of 1 year. Slabs placed in outdoor exposure, and subjected to natural freezing and then thawed with commercial flake calcium chloride, were rated for resistance to scaling at the end of two winters. Tests on a 4½-gallon 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 that have been obtained since that time. To avoid frequent repetition of the full names of the two types of cement used in the tests, portland cement, type I, will hereafter be referred to simply as portland cement (or type I); and portland blast-furnace slag cement, type IS, will be referred to as slag cement (or type IS).

Conclusions

The conclusions obtained from the results of the continued series of tests support those given in the preliminary report. All of the conclusions derived from the study are combined in this final report, and are presented in the following paragraphs.

Concrete specimens prepared with the slag cements, and continuously moist cured, had lower early strengths than those prepared with portland cements. However, at ages of 90 days and 1 year, the slag cement concretes had higher strengths, and although no tests at ages greater than 1 year were made, the ultimate strength of the slag cement concretes probably will continue to exceed those of the concretes prepared with portland cement. The same trends were shown by both the compressive and flexure strength tests.

Concretes prepared with both types of cement and subjected to intermittent curing, which included 1 or 7 days of initial moist curing, had less strength, in most cases, than duplicate concretes which were continuously moist cured until tested. 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 1 year, although the strengths of both types of concretes decreased with increasing amounts of water per bag of cement, 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 concrete prepared with slag cement, provided it is given adequate curing, will tolerate greater variations in the amount of mixing water used and still give more uniform strength than will portland cement concrete.

Concretes prepared with slag or portland cements from the same plant 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.

[1] Presented at the 40th annual meeting of the Highway Research Board, Washington, D.C., January 1961.

[2] PUBLIC ROADS, vol. 29, No. 10, October 1957, pp. 227–232.

Table 1.—Chemical composition [1] and physical properties of cements

	Source A cement		Source B cement		Source C cement		Source D cement		Source E cement	
	Type I	Type IS	Type I	Type IS	Type I	Type IS	Type I	Type IS	Type I	Type IS
Chemical composition (percent):										
Silicon dioxide	20.2	25.0	20.8	26.2	21.1	25.5	21.0	26.7	21.3	26.1
Aluminum oxide [2]	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 [3]	1.5	3.0	1.6	2.0	1.4	2.2	1.2	1.0	1.3	2.2
Sodium oxide	.08	.12	.09	.09	.04	.09	.10	.10	.15	.15
Potassium oxide	.36	.38	.15	.20	.43	.82	.17	.18	1.02	.91
Equivalent alkalies as Na_2O	.32	.37	.19	.22	.32	.61	.21	.22	.82	.75
Phosphorus pentoxide [4]	.10	.08	.03	.02	.03	.04	.09	.05	.04	.03
Manganic oxide	.53	.87	.51	.85	.03	.08	.29	.32	.07	.50
Sulfide sulfur	.09	.56	.10	.68	.01	.33	.08	1.04	.03	.40
Insoluble residue	.28	.57	.16	.73	.22	.68	.08	.20	.20	.26
Titanium dioxide	.27	.44	.24	.28	.28	.28	.18	.20	.24	.44
Free lime	.77	.26	1.20	.46	1.60	.57	.39	.19	.56	.24
Chloroform-soluble organic substances	.003	.005	.003	.006	.003	.002	.003	.005	.003	.008
Calculated compounds (percent):										
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:										
Neutral point ml	31.4	3.4	17.7	6.9	46.2	19.2	5.5	2.2	8.3	4.2
Clear point ml	44.9	4.0	23.3	8.0	68.0	26.2	6.2	.2.2	9.7	5.3
Calcium sulfate [5] in hardened mortar as SO_3 g./l	--------	.00	--------	.00	.00	.00	.00	--------	.00	.00
Physical properties:										
Apparent specific gravity	3.14	2.99	3.12	3.03	3.12	3.05	3.14	3.03	3.14	3.03
Specific surface (Blaine) cm.²/g	3810	5000	3325	4820	3425	3775	3680	4040	3555	3605
Passing No. 325 sieve percent	92.4	96.0	87.5	97.6	80.0	82.9	94.4	98.2	96.2	94.9
Autoclave expansion do	.10	.01	.06	.00	.09	.04	.07	−.02	.04	.00
Normal consistency do	25.2	27.6	23.8	27.2	20.4	22.6	26.6	31.2	26.5	26.6
Time of setting (Gilmore): Initial hours	2.9	2.8	3.7	3.4	1.7	2.6	4.2	3.5	2.9	2.8
Final do	5.1	6.8	5.6	6.2	3.4	3.9	6.5	7.9	4.8	6.2
Compressive strength (1:2.75 mortar):										
At 3 days p.s.i	2700	2555	1620	1730	1960	1740	2635	1740	2465	1525
At 7 days p.s.i	3860	4170	2625	2630	3440	2940	3940	2750	3525	2360
At 28 days p.s.i	5645	6120	4150	5190	5145	5120	5615	4615	4965	3900
Tensile strength (1:3 mortar):										
At 3 days p.s.i	295	290	280	265	265	240	305	265	320	245
At 7 days p.s.i	365	420	355	335	360	345	390	340	375	315
At 28 days p.s.i	450	500	450	445	415	425	420	460	435	455
Mortar air content percent	11.6	8.4	10.4	7.4	8.4	8.1	10.7	8.3	9.4	9.2
False set determinations (ASTM Method C359–55T):										
Initial penetration mm	50+	50+	50+	50+	50+	50+	50+	5	50+	30
5-minute penetration mm	5	4	50+	7	50+	50+	2	0	32	15
8-minute penetration mm	2	1	50+	4	50+	8	2	0	18	8
11-minute penetration mm	2	1	49	4	50+	3	1	0	14	6
Remix penetration mm	50+	50+	50+	50+	50+	50+	50+	14	50+	44
False set determinations (Federal Standard Specification No. 158, Method 2501):										
Initial penetration mm	36	40+	37	40+	40+	37	40	--------	38	36
5-minute penetration mm	18	2	30	18	7	8	31	--------	35	34
Drying shrinkage of mortar: [6]										
Shrinkage 28 days percent	.08	.10	.08	.08	.09	.10	.07	.08	.09	.10

[1] All determinations made in accordance with current ASTM methods for portland and portland blast-furnace slag cement.
[2] Values for aluminum oxide corrected for titanium and phosphorous oxides that are present.
[3] Values for type IS cements determined by ASTM Method C114–58 T, sec. 30.
[4] Determined by spectrophotometer method.
[5] Determined by ASTM Method C 265–55 T.
[6] Determined by ASTM Specification C 340–55 T.

Concretes prepared with the slag cements for both the 5½- and 6½-gallon 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 calcium chloride 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. Slag cement with a sufficiently high slag content may be suitable for use with highly alkali-reactive aggregate.

Materials and Proportions

The chemical analyses and physical properties of all cements used in the tests are given in table 1. Not included in the previous report but now presented in this table are values for phosphorous pentoxide, titanium dioxide, free lime, and calcium sulfate in hardened mortar. The values for aluminum oxide were corrected for phosphorous pentoxide and titanium dioxide and there are some slight changes, from those previously published, in the loss on ignition and in some of the calculated compound values. Table 1 also includes the results of tests for the false setting properties of the cements, using ASTM Method C 359–55 T and Federal Standard Specification No. 158, Method 2501; and drying shrinkage tests on mortars, using ASTM Spec. C 340–55 T.

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

The mixes were designed on a water-cement ratio basis for air-entrained concrete having 5½-percent air, 2- to 3-inch slump, and a b/b_0 (workability factor) 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 gallons per bag of cement. With one exception, the same mix proportions were used for all mixes having the same water content. This exception was the mix containing 6½ gallons 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 the use of a commercial solution of neutralized Vinsol resin. The average amount of air-entraining solution needed for 5½-percent air for the

Table 2.—Grading and physical properties of the aggregates

Grading and physical properties	White Marsh sand	Riverton limestone
Grading: Percentage passing sieves:		
1-inch	------	100
¾-inch	------	70
½-inch	------	40
⅜-inch	100	24
No. 4	96	0
No. 8	79	------
No. 16	66	------
No. 30	50	------
No. 50	23	------
No. 100	7	------
Fineness modulus	2.79	7.06
Physical properties:		
Bulk specific gravity:		
Dry	2.63	2.78
Saturated surface dry	2.65	2.79
Absorption .... percent	0.4	0.4
Strength ratio (Ottawa sand):		
Compressive strength:		
At 7 days .. percent	158	------
At 28 days .... do	167	------
Tensile strength:		
At 7 days ..... do	106	------
At 28 days .... do	116	------
Los Angeles wear test, grading A, loss .... percent	------	20.2
Accelerated soundness, Na_2SO_4, loss ..... percent	------	3.5

concretes containing the slag cements was the same as was used with the portland cements from sources C and E, 1½ times as much for those from sources A and D, and 2½ times as much as that from source B.

Mixing, Molding, and Curing of Specimens

The mixing, molding, curing, and testing of specimens was done in accordance with the applicable AASHO or ASTM methods. All mixing was done in an open pan-type laboratory mixer of 1¾-cubic foot capacity. Both fine and coarse aggregates were used in a wet condition and the amount of mixing water needed for each batch of concrete was corrected for the free water in the aggregates. The following mixing procedure was employed: The cement and the wet sand were mixed for 30 seconds and part of the required amount of water and all of the air-entraining solution were then added and mixed for 30 seconds. The wet coarse aggregate was then added, with the necessary amount of additional water. The concrete was mixed for 2½ minutes after the addition of the coarse aggregate. Determinations were made of the slump and unit weight, and of air content by the pressure method. The portions of the concrete used for the slump and unit weight tests were returned to the concrete in the mixer, and were remixed for 15 seconds before the test specimens were prepared.

All beams were made in individual molds. Beams and cylinders that were to be tested after continuous moist curing were molded, cured, and tested in accordance with applicable AASHO procedures.

Beams for freezing and thawing in water by the slow cycle procedure described in ASTM Method C 292 were moist cured for 7 days, cured for 14 days in laboratory air at 73° F. and 50-percent relative humidity, and immersed for 7 days in water at 73° F.

Cylinders and beams that were cured intermittently for strength tests, and beams that were cured intermittently for shrinkage tests, were stored in moist air or water at 73° F. and in laboratory air at 73° F. and 50-percent relative humidity.

Specimen slabs 16 by 24 by 4 inches were made for outdoor exposure to determine the resistance of the concrete to scaling caused by freezing and the removal of ice by calcium chloride. A raised edge was cast around the perimeter of each slab. After being moist cured for 28 days under standard conditions, the slabs were placed in the exposure plot for freezing.

During mixing, premature stiffening was noted in several of the mixes containing slag cement. Tests had been made in accordance with ASTM Method C 359–55 T and Federal Standard Specification No. 158, Method 2501, to measure this false setting of the cement, and their results are given at the bottom of table 1. The false set is indicated in the ASTM procedure by loss of nearly all of the penetration during the 11-minute test period, while in the Federal method a difference between initial and final penetration of more than 17 millimeters after 5 minutes is considered to be an indication of false set. The two methods can be considered as indicating that both types of cement from source A are false setting cements, and that those from source E do not have 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. While 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 the intermittently cured specimens are shown in tables 4–7 and in figures 1–3. Data for the sonic and static moduli of elasticity are shown in tables 8 and 9. The average values for drying shrinkage tests are shown in table 10 and in figure 4, and the laboratory freezing and thawing data are shown in table 11 and in figure 5. These tables and figures are similar to those included in the preliminary report except that these present complete data. Additional data are given in two new tables: Table 12 contains the results of tests on concrete slabs subjected to outdoor freezing and subsequent thawing by the use of calcium chloride; and table 13 gives the results of the mortar bar expansion tests for alkali-aggregate reaction.

These data are discussed in the following text by comparing the results of tests of concrete containing slag cement with those of concrete containing portland cement. In the discussion, emphasis is given to the results not covered in the preliminary report.

Compressive Strength

Table 4 shows the results of the compressive strength tests of the concretes (moist cured until tested) containing the portland cements and the slag cements from the five sources. Each value in the table is the average of five tests made on 6- by 12-inch cylinders. Mixes

Table 3.—Mix data for laboratory specimens [1]

Cement		4½ gal. of water per bag of cement				5½ gal. of water per bag of cement				6½ gal. of water per bag of cement				7½ gal. of water per bag of cement			
Source	Type	Cement content	Slump	Air	Vinsol resin added	Cement content	Slump	Air	Vinsol resin added	Cement content	Slump	Air	Vinsol resin added	Cement content	Slump	Air	Vinsol resin added
		Bags/cu. yd.	*Inches*	*Percent*	*Ml./bag*	*Bags/cu. yd.*	*Inches*	*Percent*	*Ml./bag*	*Bags/cu. yd.*	*Inches*	*Percent*	*Ml./bag*	*Bags/cu. yd.*	*Inches*	*Percent*	*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	[2] 5.14	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

[1] Each value is an average of 5 tests. Proportions by oven-dry weight (except as indicated in footnote 2): 4½-gallon mix=94–135–255, 5½-gallon mix=94–190–315, 6½-gallon mix=94–255–390, and 7½-gallon mix=94–325–460.

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

Table 4.—Compressive strength tests on moist-cured specimens [1]

Cement		4½ gallons of water per bag of cement: Compressive strength after—					5½ gallons of water per bag of cement: Compressive strength after—				
Source	Type	3 days	7 days	28 days	90 days	1 year	3 days	7 days	28 days	90 days	1 year
		p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*
A	I	3, 440	5, 050	6, 730	7, 590	8, 700	2, 610	4, 030	5, 620	6, 440	6, 840
A	IS	3, 310(96)	4, 890(97)	7, 370(110)	8, 360(110)	9, 360(108)	2, 340(90)	3, 810(95)	5, 940(106)	7, 140(111)	7, 840(115)
B	I	2, 670	4, 570	6, 720	7, 830	8, 400	1, 940	3, 330	5, 400	6, 380	6, 730
B	IS	2, 800(105)	4, 280(94)	7, 250(108)	8, 870(113)	9, 850(117)	1, 940(100)	3, 020(91)	5, 790(107)	7, 640(120)	8, 490(126)
C	I	3, 010	4, 770	6, 060	7, 040	8, 080	2, 070	3, 710	5, 070	5, 500	6, 130
C	IS	2, 430(81)	4, 240(89)	6, 270(103)	7, 510(107)	8, 430(104)	1, 720(83)	3, 220(87)	5, 320(105)	6, 390(116)	7, 070(115)
D	I	3, 610	5, 270	6, 940	7, 610	8, 750	2, 650	4, 160	6, 050	6, 920	7, 310
D	IS	2, 750(76)	4, 200(80)	7, 210(104)	8, 340(110)	9, 680(111)	2, 110(80)	3, 390(81)	6, 150(102)	7, 600(110)	8, 330(114)
E	I	3, 530	5, 000	6, 200	6, 770	7, 520	2, 680	4, 150	5, 660	6, 240	6, 820
E	IS	2, 480(70)	3, 440(69)	5, 580(90)	6, 290(93)	7, 490(100)	1, 830(68)	2, 790(67)	4, 460(79)	5, 900(95)	6, 740(99)
Average, type I		3, 250	4, 930	6, 530	7, 370	8, 290	2, 390	3, 880	5, 560	6, 300	6, 700
Average, type IS		2, 750(85)	4, 210(85)	6, 740(103)	7, 870(107)	8, 960(108)	1, 990(83)	3, 250(84)	5, 530(99)	6, 930(110)	7, 690(114)

Cement		6½ gallons of water per bag of cement: Compressive strength after—					7½ gallons of water per bag of cement: Compressive strength after—				
Source	Type	3 days	7 days	28 days	90 days	1 year	3 days	7 days	28 days	90 days	1 year
		p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*
A	I	2, 050	3, 260	4, 670	5, 440	5, 590	1, 500	2, 350	3, 710	4, 130	4, 200
A	IS	1, 770(86)	3, 060(94)	4, 960(106)	6, 170(113)	6, 910(124)	1, 320(87)	2, 250(96)	3, 780(102)	4, 720(114)	5, 310(126)
B	I	1, 510	2, 580	4, 180	5, 190	5, 640	1, 000	1, 740	2, 980	3, 620	3, 800
B	IS	1, 440(95)	2, 310(90)	4, 560(109)	6, 460(124)	7, 160(127)	1, 070(107)	1, 770(102)	3, 700(124)	4, 970(137)	5, 770(152)
C	I	1, 770	2, 950	4, 100	4, 650	4, 920	1, 320	2, 240	3, 250	3, 640	3, 820
C	IS	1, 360(77)	2, 430(82)	4, 240(102)	5, 030(108)	5, 870(119)	1, 010(77)	1, 810(81)	3, 160(97)	3, 870(106)	4, 350(114)
D	I	2, 180	3, 400	4, 970	5, 780	6, 110	1, 600	2, 350	3, 810	4, 580	4, 640
D	IS	1, 630(75)	2, 440(72)	4, 860(98)	6, 110(106)	7, 060(116)	1, 230(77)	2, 120(90)	3, 670(96)	4, 720(103)	5, 360(116)
E	I	2, 200	3, 310	4, 790	5, 320	5, 460	1, 750	2, 760	3, 860	4, 150	4, 190
E	IS	1, 350(61)	2, 220(67)	3, 680(77)	4, 770(90)	5, 820(106)	1, 010(58)	1, 620(59)	2, 780(72)	3, 600(87)	4, 390(105)
Average, type I		1, 940	3, 100	4, 540	5, 280	5, 540	1, 430	2, 290	3, 520	4, 020	4, 130
Average, type IS		1, 510(78)	2, 490(80)	4, 460(98)	5, 710(108)	6, 560(118)	1, 130(79)	1, 910(83)	3, 420(97)	4, 380(109)	5, 040(122)

[1] Figures in parentheses represent ratios (in percent) of the strength of the concrete containing type IS cement to the strength of the corresponding concrete containing type I cement Each value is an average of 5 tests. Specimens, capped with neat Lumnite cement, were 6- by 12-inch cylinders stored in moist air until tested.

containing 4½, 5½, 6½, and 7½ gallons of water per bag of cement were tested at ages of 3, 7, 28, 90, and 365 days. The ratios (expressed as percentages) of the strengths of the concretes prepared with the slag cements to the strengths of the concretes 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 solid lines) in figure 1.

The data in table 4 show 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 3 of the 48 cases, than concretes prepared with the portland cements from the same four sources. Concrete prepared with slag cement from source E had lower compressive strengths at all ages up to and including 90 days than the corresponding concrete prepared with the portland cement, but 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 were 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

The results of the flexural strength tests of the concretes (moist cured until tested), prepared with the portland cements and the slag cements from the five sources, are given in table 5. Each value is the average of five tests made on 6- by 6- by 21-inch beams. Mixes containing 4½, 5½, 6½, and 7½ gallons of water per bag of cement were tested at 3, 7, 28, 90, and 365 days. The ratios (expressed as percentages) 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 (from all sources) prepared with the slag cements with concretes prepared with the portland cements are shown for each mix (in dashed lines) in figure 1.

Approximately the same trends developed for flexural strength as for compressive strength. In most cases the concrete 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 cemen concrete in all cases but one. Concretes prepared with the slag cement from source E ha lower strengths at 28 days, but equal or greate strengths at 90 and 365 days, than corre sponding portland cement concretes.

The average flexural strength of the con cretes prepared with the slag cements from th five sources, as shown in figure 1, was lowe at 3 and 7 days but higher at 28, 90, and 36 days than that for the concretes prepared wit the portland cements.

Effect of Water Content

The relations between the strengths of con cretes prepared with the two types of cement were not much affected by changes in wate content. At 3, 7, 28, and 90 days there wa little difference between the strength ratio for the 4½- and the 7½-gallon mixes. At 3 7, and 28 days there was a slight decrease i strength ratios with increases in the water while at 90 days there was a slight increase in the strength ratios. At 1 year, the per centage increase in strength of the slag cemen concrete over the portland cement concret became greater with each increase in wate content. In figure 2, the ratios of the averag strength of the slag cement concretes at eac age tested (combined for all five sources) t the average strength of the portland cemen concretes at the same age are plotted agains the water content of the concretes. It will be observed that, for both compressive and flexural strengths, at ages through 90 days there was little difference in the strength ratios for the different mixes. At 1 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 1 year, of the concrete prepared with slag cement were less affected by 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 shown in tables 6 and 7, and average values for all cements are shown in figure 3. One mix, containing 5½ gallons of water per bag of cement, was used in these tests. Three groups of intermittently cured specimens were tested at 28 days and two groups at 90 days.

Of those tested at 28 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. The second group was moist cured for 1 day, followed by 26 days storage in laboratory air, 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, then immersed in water 1 day, and tested wet.

The fourth group, one of the two tested at 90 days, was moist cured for 1 day, followed by 88 days in laboratory air, then immersed in water 1 day, and tested wet. The fifth group was moist cured for 7 days, followed by 82 days in laboratory air, then immersed in water 1 day, and tested wet.

The results of the compressive strength tests on these specimens and on specimens continuously moist cured for the same time period (28 and 90 days) are given in table 6. The ratios (expressed as percentages) of the compressive strengths of the intermittently cured specimens to the strengths of duplicate continuously moist-cured specimens are also given.

Of the 28-day specimens, those in group 1 showed (fig. 3) 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 continuously moist-cured specimens. Group 2 showed a loss in strength of 36 percent for the portland cement concrete and 41 percent for the slag cement concrete. Group 3 showed losses of 10 and 13 percent, respectively. Most of the 28-day specimens prepared with portland cements and intermittently cured showed a smaller average reduction in compressive strength than similarly cured specimens prepared with slag cements. However, these differences were very slight. The specimens in group 1 had higher strengths for both the portland and the slag cement concretes than the specimens in group 2.

Of the 90-day specimens, those in group 4 showed an average reduction in strength of 44 percent for the portland cement concrete and 52 percent for the slag cement concrete. Those in group 5 showed losses of 22 and 28 percent, respectively. All of the 90-day intermittently cured specimens prepared with portland cement showed less reduction in strength than the corresponding specimens prepared with slag cement. The average percentage reduction in compressive strength for the slag cement specimens tested at 90 days was greater than for the similarly cured slag cement specimens tested at 28 days.

For the intermittently cured specimens of the portland cement concretes and the slag cement concretes which were moist cured the same length of time, the actual compressive strengths 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.

The results of tests for flexural strength of intermittently cured specimens are shown in table 7. These data indicate the same general trends as were shown for compressive strength. The portland cement concretes showed 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 was 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 testing as the concrete which was moist cured continuously for 28 days. The 90-day tests did not show this feature.

The average results of these tests of intermittent curing are summarized in figure 3. The tests 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,

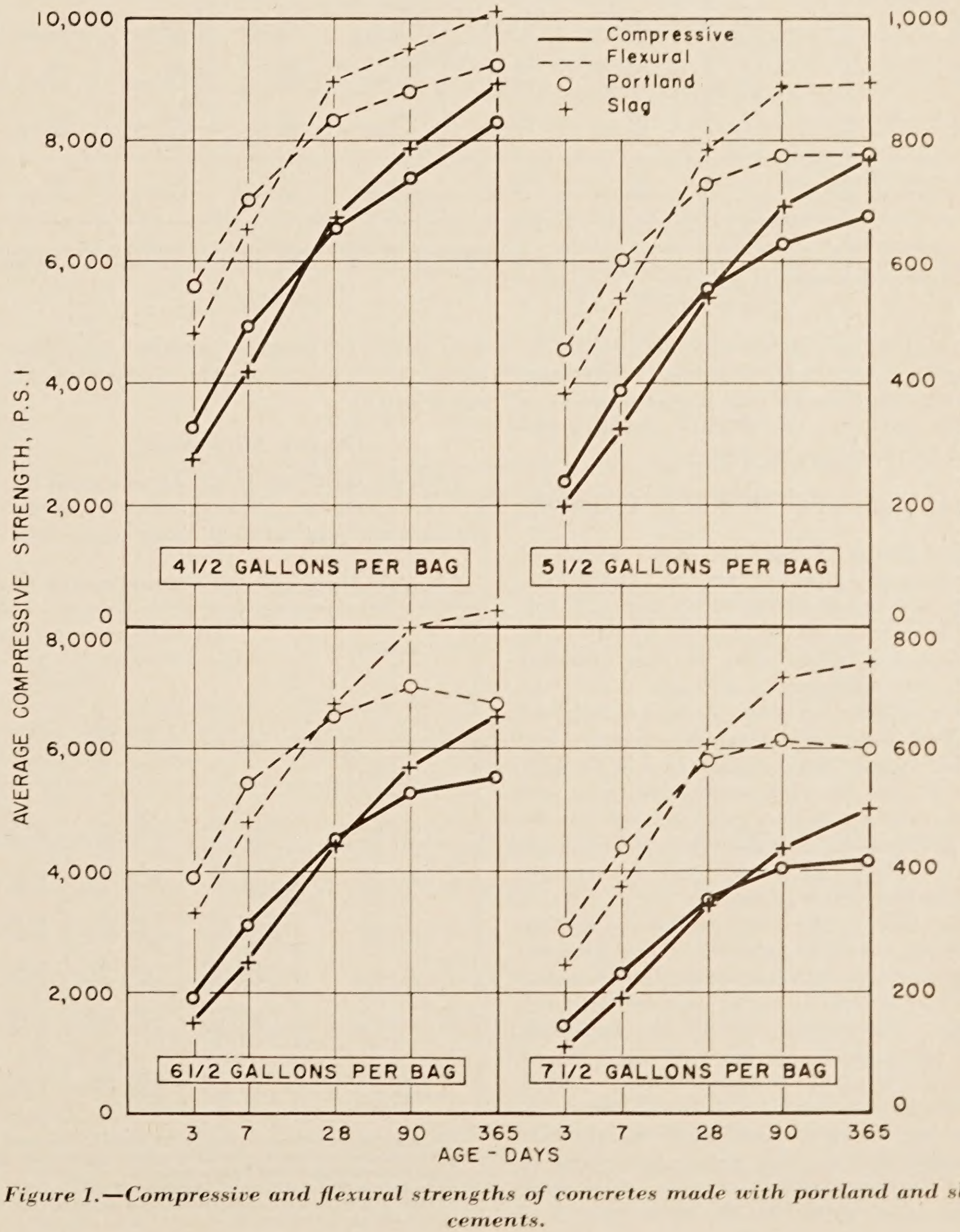

Figure 1.—Compressive and flexural strengths of concretes made with portland and slag cements.

Table 5.—Flexural strength tests on moist-cured specimens [1]

Cement: Source	Cement: Type	4½ gallons of water per bag of cement: Flexural strength after— 3 days	7 days	28 days	90 days	1 year	5½ gallons of water per bag of cement: Flexural strength after— 3 days	7 days	28 days	90 days	1 year
		p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*
A	I	575	700	855	895	955	495	605	730	760	775
A	IS	545(95)	735(105)	925(108)	1,005(112)	1,090(114)	420(85)	610(101)	880(121)	920(121)	925(119)
B	I	505	680	790	915	910	380	570	740	790	810
B	IS	495(98)	635(93)	885(112)	975(106)	1,020(112)	395(104)	520(91)	750(101)	885(112)	935(115)
C	I	500	685	785	780	885	410	550	630	695	690
C	IS	460(92)	705(103)	955(122)	915(117)	950(107)	365(89)	550(100)	730(116)	815(117)	815(118)
D	I	590	705	850	895	955	500	610	750	780	810
D	IS	485(82)	630(89)	875(103)	950(106)	1,020(107)	400(80)	525(86)	775(103)	925(119)	935(115)
E	I	595	740	890	930	905	495	670	805	855	790
E	IS	445(75)	605(82)	875(98)	930(100)	1,010(112)	375(76)	505(75)	790(98)	915(107)	895(113)
Average, type I		555	700	835	885	920	455	600	730	775	775
Average, type IS		485(87)	660(94)	905(108)	955(108)	1,020(111)	390(86)	540(90)	785(108)	890(115)	900(116)

Cement: Source	Cement: Type	6½ gallons of water per bag of cement: Flexural strength after— 3 days	7 days	28 days	90 days	1 year	7½ gallons of water per bag of cement: Flexural strength after— 3 days	7 days	28 days	90 days	1 year
		p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*
A	I	420	560	635	695	655	315	425	590	605	580
A	IS	365(87)	535(96)	715(113)	800(115)	820(125)	270(86)	435(102)	660(112)	730(121)	770(133)
B	I	330	485	695	760	720	240	370	520	645	610
B	IS	305(92)	440(91)	690(99)	800(105)	825(114)	235(98)	365(99)	640(123)	780(121)	815(134)
C	I	345	505	565	600	615	270	430	530	530	540
C	IS	315(91)	475(94)	690(122)	775(129)	755(123)	220(81)	355(83)	555(105)	630(119)	650(120)
D	I	435	555	640	720	690	335	455	600	625	645
D	IS	345(79)	485(87)	730(114)	835(116)	870(126)	275(82)	395(82)	630(105)	760(122)	750(116)
E	I	440	620	730	745	700	355	490	670	635	615
E	IS	310(70)	445(72)	610(84)	780(105)	850(121)	225(63)	340(69)	540(81)	650(102)	745(121)
Average, type I		395	545	655	705	675	305	435	580	610	600
Average, type IS		330(84)	475(87)	685(105)	800(113)	825(122)	245(80)	380(87)	605(104)	710(116)	745(124)

[1] Figures in parentheses represent ratios (in percent) of the strength of concrete containing type IS cement to the strength of the corresponding concrete containing type I cement. Eac value is an average of 5 tests. Specimens, stored in moist air until tested, were 6- by 6- by 21-inch beams tested in accordance with ASTM Method C-78 with third point loading on a 18-inch span; side as molded in tension.

desirable to cure all concrete as perfectly as possible. Apparently somewhat more care must be exercised for slag cement concrete to ensure obtaining the desirable features furnished by this type of cement.

Sonic and Static Moduli of Elasticity

The results of tests for sonic moduli of elasticity are given in table 8. Determinations were made on the 6- by 6- by 21-inch beams prior to tests for flexural strength. In general, the same trends as were obtained with the compressive strength tests were shown by the sonic tests. 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 concrete had higher average sonic moduli (except for the 4½-gallon mix). The difference in moduli for the two types of cement was not great—usually less than 5 percent.

The data for the static moduli of elasticity tests are shown in table 9. These data are limited to tests at each age for the 4½-gallon mix and to tests at 1 year only for the other mixes. (The static moduli test apparatus was not available for the early age tests on the 5½-, 6½-, and 7½-gallon mixes.) Determinations were made on 6- by 12-inch cylinders by use of an autographic stress-strain recorder with a 6-inch gage length, prior to tests for compressive strength. 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 in drying were made on concrete specimens prepared with each of the portland and slag cements, using mixes with 5½ and 6½ gallons of water per bag of cemen The specimens were 3- by 4- by 16-inch beam with gage studs cast in each end. Thre beams prepared with each cement and wate content were moist cured for 2 days and thre sets were moist cured for 7 days prior to th beginning of the measurements for shrinkage The specimens were stored in room air a

Table 6.—Compressive strength tests on specimens cured intermittently [1]

Cement: Source	Cement: Type	5½ gallons of water per bag of cement: Compressive strength after curing for— 28 days: 1 day moist, 27 days dry [2]	28 days: 1 day moist, 26 days dry, 1 day soak [2]	28 days: 7 days moist, 20 days dry, 1 day soak [2]	28 days: 28 days moist [3]	90 days: 1 day moist, 88 days dry, 1 day soak [2]	90 days: 7 days moist, 82 days dry, 1 day soak [2]	90 days: 90 days moist [3] [4]
		p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*
A	I	4,420 (77)	3,980 (69)	5,100 (88)	5,770	4,000 (62)	5,140 (80)	6,440
A	IS	4,080 (69)	3,760 (63)	5,360 (90)	5,940	3,620 (51)	5,450 (76)	7,140
B	I	3,420 (63)	3,050 (56)	4,660 (86)	5,400	3,190 (50)	4,850 (76)	6,380
B	IS	4,000 (67)	3,270 (55)	4,790 (81)	5,950	3,690 (48)	4,950 (65)	7,640
C	I	3,320 (64)	3,030 (59)	4,720 (91)	5,160	2,970 (54)	4,490 (82)	5,500
C	IS	3,180 (61)	2,840 (55)	4,490 (86)	5,200	2,840 (44)	4,620 (72)	6,390
D	I	4,140 (72)	3,620 (62)	5,260 (91)	5,790	3,810 (55)	5,160 (75)	6,920
D	IS	4,050 (69)	3,450 (59)	5,010 (86)	5,830	3,520 (46)	5,270 (69)	7,600
E	I	4,040 (75)	3,820 (70)	4,960 (92)	5,420	3,850 (62)	4,990 (80)	6,240
E	IS	3,700 (80)	2,870 (62)	4,180 (91)	4,600	2,990 (51)	4,660 (79)	5,900
Average, type I		3,870 (70)	3,500 (64)	4,940 (90)	5,510	3,560 (56)	4,930 (78)	6,300
Average, type IS		3,800 (69)	3,240 (59)	4,770 (87)	5,500	3,330 (48)	4,990 (72)	6,930

[1] Figures in parentheses represent the ratios (in percent) of the strength of the intermittently cured specimens (6- b 12-inch cylinders) to the strength of the continuously moist-cured specimens. Each value is an average of 5 tests.
[2] Specimens capped with sulfur cement.
[3] Specimens capped with neat Lumnite cement.
[4] These specimens were made on different days than the 90-day specimens which were cured intermittently. These ar the same values as given in table 4.

73° F. and 50-percent relative humidity for 90 days, and length measurements were made frequently. The specimens were then immersed in water at room temperature for 14 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 gallons of water per bag of cement are shown in figure 4, and the shrinkages 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 among the concrete specimens prepared with the two types of cement were too small to be significant. It appears that concern over the shrinkage of concrete prepared with slag cement is unfounded. The result of the drying shrinkage tests of mortar bars, ASTM Spec. C 340–55 T, shown at the bottom of table 1, supports the same conclusion.

Laboratory Freezing and Thawing

Freezing and thawing tests were made on both slag and portland cement concretes prepared with 5½ and 6½ gallons of water per bag of cement. Beams measuring 3 by 4 by 16 inches were moist cured for 7 days, followed by 14 days of storage in laboratory air, and then immersed in water for 7 days prior to freezing. Freezing and thawing was in accordance with ASTM Method C 292 for slow freezing and thawing in water. The results of these tests and the durability factors of the concretes are given in table 11 and are shown in figure 5. The durability factor was calculated as follows:

$$DF = (P \times N) \div M$$

Where:

DF = durability factor.

P = relative dynamic modulus of elasticity at N cycles, in percent (60-percent minimum).

N = number of cycles at which P reached 60 percent or 300, whichever is less.

M = 300 (cycles).

These tests show 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 with Calcium Chloride

In testing the effects of calcium chloride when used for ice removal on portland and slag cement concretes, three mixes were used, containing 5½, 6½, and 7½ gallons of water per bag of cement. Concrete slabs 16 inches wide, 24 inches long, and 4 inches deep were prepared with each type of 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. The slabs were in the exposure area for about 6 months before freezing weather began.

When freezing was expected, the top surface of each specimen was covered with one-fourth

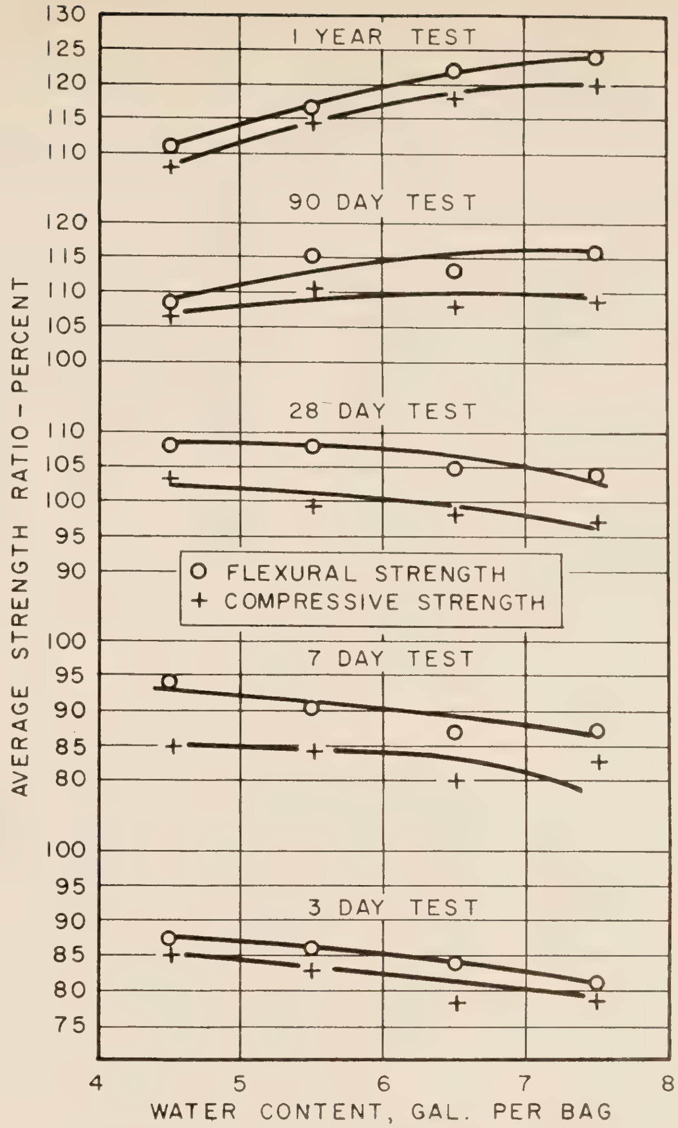

Figure 2.—Effect of water content on ratio of strength of slag cement concrete to strength of portland cement concrete.

Table 7.—Flexural strength tests on specimens cured intermittently [1]

Cement		5½ gallons of water per bag of cement: Flexural strength after curing for—						
		28 days				90 days		
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 [2]
		p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*
A	I	435 (58)	565 (76)	715 (96)	745	600 (79)	710 (93)	760
A	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
B	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
C	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
D	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
E	IS	435 (55)	465 (59)	720 (91)	790	445 (49)	725 (79)	915
Average, type I		460 (62)	510 (69)	745 (101)	740	505 (65)	730 (94)	775
Average, type IS		450 (56)	490 (61)	755 (94)	800	470 (53)	750 (84)	890

[1] Figures in parentheses represent the ratios (in percent) of the strength of the intermittently cured specimens to the strength of the moist-cured specimens. Each value is an average of 5 tests. Specimens were 6- by 6- by 21-inch beams tested in accordance with ASTM Method C 78 with third point loading on an 18-inch span; side as molded in tension.

[2] These specimens were made on different days than the 90-day specimens which were cured intermittently. These are the same values as given in table 5.

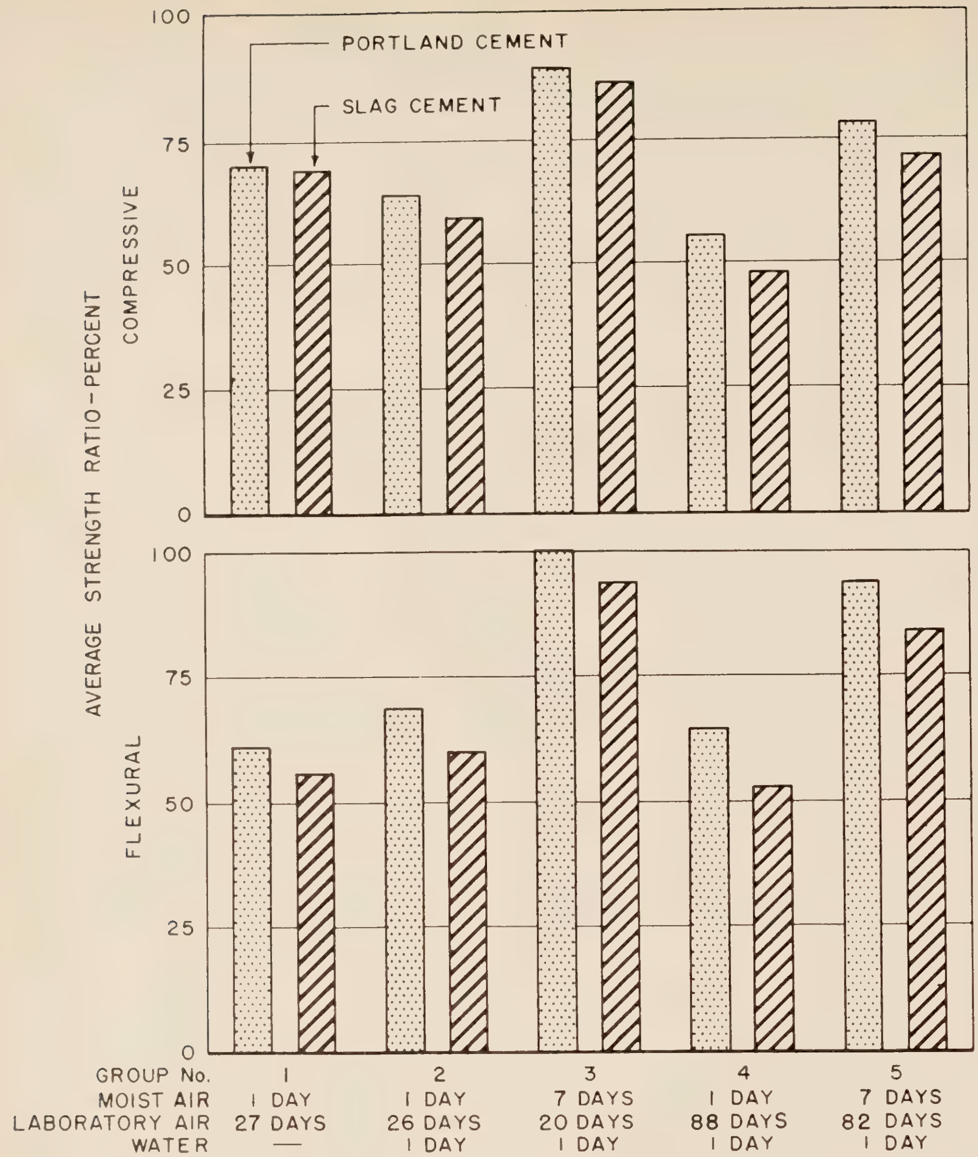

Figure 3.—Strengths of intermittently cured portland and slag cement concretes expressed as ratios of strengths of duplicate continuously moist-cured concretes.

to one-half inch of water. Each morning after the water had frozen, flake calcium chloride was spread over the ice at a rate of 2.4 pounds per square yard of ice-encrusted surface. After the ice had thawed, usually about 3 hours later, the calcium-chloride solution was washed off and the surface was again covered with fresh water. The tests were continued through two winters, with a total of 55 cycles of freezing and thawing.

The slabs were examined periodically and rated by visual observation according to the amount and depth of scaling of the exposed surface. A rating of zero indicated that no scaling had occurred, and a rating of 10 indicated deep scaling over the entire surface of the specimen. A summary of the ratings is shown in table 12.

These tests showed very little difference between the behavior of the portland cement concrete and that of the slag cement concrete. However, considerable differences were found among the cements, both portland and slag, prepared by the different plants, and used in concretes containing 5½ gallons 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 the other concretes. When a water content of 6½ or 7½ gallons per bag was used, severe scaling was found on all specimens. It is apparent that the water content of the concrete is of primary importance in the scaling of concrete caused by de-icing agents. Only when the water content is kept at a low value can differences in the quality of the concrete caused by other factors influence the results obtained.

Mortar Bar Expansion Tests

The alkali-reactivity of both the portland and slag cements was evaluated by the mortar bar tests, as 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-inch

Table 8.—Sonic modulus of elasticity [1]

Cement		Sonic modulus of elasticity—pounds per square inch × 10^6																							
		4½ gallons of water per bag of cement						5½ gallons of water per bag of cement						6½ gallons of water per bag of cement						7½ gallons of water per bag of cement					
Source	Type	3 days	7 days	28 days	90 days	180 days	1 year	3 days	7 days	28 days	90 days	180 days	1 year	3 days	7 days	28 days	90 days	180 days	1 year	3 days	7 days	28 days	90 days	180 days	1 year
A	I	5.44	6.01	6.64	6.78	7.07	7.25	----	----	6.38	6.76	6.82	6.92	4.95	5.73	6.32	6.66	6.80	6.68	4.18	5.22	5.80	6.07	6.15	6.18
A	IS	5.22	5.38	6.19	6.75	7.01	7.10	----	----	6.17	6.70	6.84	6.91	4.79	5.45	6.04	6.71	6.92	6.87	3.85	4.86	5.72	6.16	6.63	6.66
B	I	4.99	5.70	6.51	6.83	6.95	7.05	----	5.70	6.46	6.52	6.62	6.69	4.44	5.44	6.19	6.57	6.70	6.60	3.66	4.84	5.62	6.00	----	6.13
B	IS	5.03	5.52	6.43	6.95	7.13	7.21	----	4.95	6.11	6.72	6.91	7.09	4.26	4.97	5.86	6.41	6.71	6.78	3.59	4.61	5.51	6.27	----	6.54
C	I	5.28	6.40	6.56	6.57	6.82	6.93	----	5.75	6.33	6.55	6.69	6.78	4.62	5.57	6.15	6.33	6.46	6.52	3.99	5.06	5.83	5.98	----	6.02
C	IS	5.01	6.25	6.39	6.51	6.94	6.99	----	5.65	6.39	6.57	6.67	6.80	4.38	5.42	6.20	6.57	6.76	6.72	3.65	4.72	5.73	6.20	----	6.40
D	I	5.22	6.05	6.60	6.86	7.25	7.01	----	6.08	6.43	6.69	6.75	6.82	4.91	5.69	6.27	6.59	6.72	6.61	4.36	5.19	5.89	6.04	----	6.15
D	IS	4.97	5.68	6.54	6.85	7.00	7.02	----	5.95	6.65	7.01	7.18	7.28	4.66	5.35	6.22	6.63	6.89	6.80	4.00	4.76	5.82	6.33	----	6.42
E	I	5.58	6.12	6.71	6.90	6.94	6.96	----	6.20	6.65	6.78	6.95	7.07	5.06	5.84	6.45	6.69	6.77	6.66	4.56	5.51	6.15	6.19	----	6.23
E	IS	4.95	5.38	6.15	6.50	6.76	6.96	----	5.57	6.27	6.54	6.91	7.19	4.58	5.30	5.97	6.59	6.81	6.84	3.94	4.73	5.67	6.11	----	6.42
Average, type I		5.30	6.06	6.60	6.79	7.01	7.04	----	5.93	6.45	6.66	6.77	6.86	4.80	5.65	6.28	6.57	6.69	6.61	4.15	5.16	5.86	6.06	----	6.14
Average, type IS		5.04	5.64	6.34	6.71	6.97	7.06	----	5.53	6.32	6.71	6.90	7.05	4.53	5.47	6.06	6.58	6.82	6.80	3.81	4.74	5.69	6.21	----	6.49

[1] Sonic modulus determined on 6- by 6- by 21-inch beams prior to testing for flexural strength. Specimens were continuously moist cured. Each value is an average of 5 tests.

Table 9.—Static modulus of elasticity [1]

Cement		Static modulus of elasticity—pounds per square inch × 10⁶							
		For mixes with 4½ gallons of water per bag of cement					At 1 year,[2] for mixes with water content per bag of cement of—		
Source	Type	3 days	7 days	28 days	90 days	1 year	5½ gal.	6½ gal.	7½ gal.
A	I	4.82	5.89	6.24	6.69	6.66	6.74	6.26	5.70
A	IS	4.63	5.70	6.28	6.86	6.85	6.65	6.68	6.60
B	I	4.53	5.70	6.01	6.65	6.83	6.42	6.48	5.69
B	IS	4.11	5.67	6.63	7.14	6.96	6.62	6.92	6.70
C	I	4.30	5.52	5.92	6.51	6.68	6.42	6.21	5.74
C	IS	4.31	5.61	5.95	6.59	6.76	6.34	6.73	6.19
D	I	4.81	5.91	6.26	6.20	6.65	6.43	6.54	6.26
D	IS	4.38	4.88	7.30	6.93	6.96	7.12	6.70	6.77
E	I	4.90	6.31	6.82	6.39	6.74	6.90	6.69	5.56
E	IS	4.81	5.29	6.06	6.34	6.84	6.60	6.99	6.45
Average, type I		4.67	5.87	6.25	6.49	6.71	6.58	6.44	5.79
Average, type IS		4.45	5.43	6.44	6.77	6.87	6.67	6.80	6.54

[1] Static modulus determined on 6- by 12-inch cylinders prior to testing for compressive strength. Specimens were continuously moist cured. Each value is an average of 5 tests.
[2] No tests were made at 90 days or less since the static modulus test apparatus was not available during that period of the test program.

Table 10.—Drying shrinkage of concrete

Water content	Initial moist curing	Final shrinkage [1]	
		Portland cement concrete	Slag cement concrete
Gal./bag	*Days*	*Percent*	*Percent*
5½	2	0.040	0.041
5½	7	.038	.040
6½	2	.042	.037
6½	7	.040	.039

[1] Shrinkage after 2 cycles of drying for 60 days and 14 days immersion in water, followed by an additional 60 days drying.

mortar specimens prepared with crushed and graded Pyrex glass. The principal difference between the Federal and the ASTM tests is the use of a significantly higher water-cement ratio in the latter. In addition, a modified mortar bar test was made, using the same size of specimen. This was prepared from a 1:2 mortar containing ASTM C 109 Ottawa sand with various amounts of No. 8- to No. 30-size reactive opal, ranging up to 2 percent, and having a water-cement ratio of 0.50. 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 portland cements from sources C and E would be considered as potentially expansive by both the Federal and ASTM procedures, but the portland cement from source A would be similarly classified only by the ASTM procedure. None of the slag 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 shown 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, in which 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 portland cements from sources A, C, and E and the slag cements from sources C and E. For the cements from sources A, B, D, and E, the expansions of the slag cements were less than those for the portland cements, but the slag cement from source C showed a greater expansion than the portland cement from that source. It should be noted that for this source, the alkali content of the slag cement was nearly double that of the portland 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 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 slag cements is not entirely effective in preventing expansion resulting from the alkali-aggregate reaction under the conditions of this test.

It was noted that two of the slag cements had an equivalent alkali content, as shown in table 1, of over 0.6 percent, which would cause them to be classified as high-alkali cements. It was also noted, in the modified method of

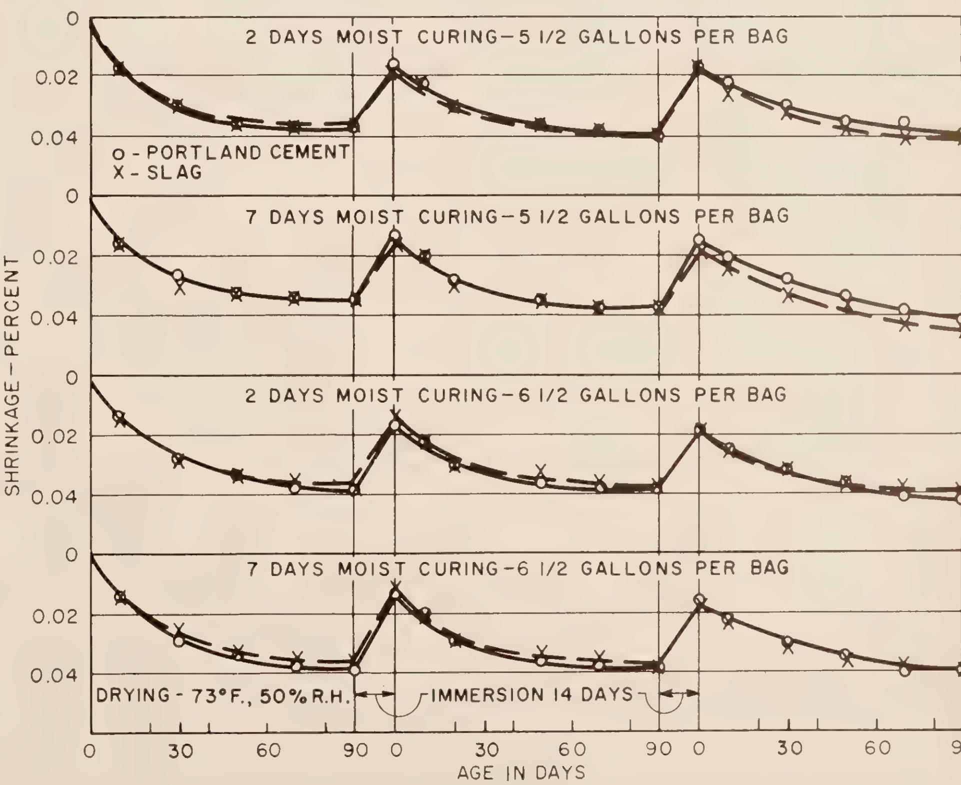

Figure 4.—Rate of drying shrinkage of portland and slag cement concretes.

Table 11.—Results of laboratory freezing and thawing tests[1]

Cement		5½ gallons of water per bag of cement									6½ gallons of water per bag of cement								
Source	Type	Percent of original N^2 after freezing and thawing for indicated cycles								Durability factor	Percent of original N^2 after freezing and thawing for indicated cycles								Durability factor
		10 cycles	20 cycles	50 cycles	100 cycles	150 cycles	200 cycles	250 cycles	300 cycles		10 cycles	20 cycles	50 cycles	100 cycles	150 cycles	200 cycles	250 cycles	300 cycles	
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
Average, type I										64									51
Average, type IS										88									66

[1] Specimens were 3- by 4- by 16-inch 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 or 5 beams.

test when 1 percent of opal was used, that mortar prepared with the slag cement with the greatest amount of alkali did not develop the most expansion at an age of 1 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. It was learned from the manufacturers that the slag 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.

In order to take this into account, figure 6 was prepared. This shows 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 content of each cement by the equivalent alkali content expressed as sodium oxide. The curve in the figure shows 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 the slag content of a slag cement appreciably higher than 30 percent, to prevent the alkali-aggregate reaction.

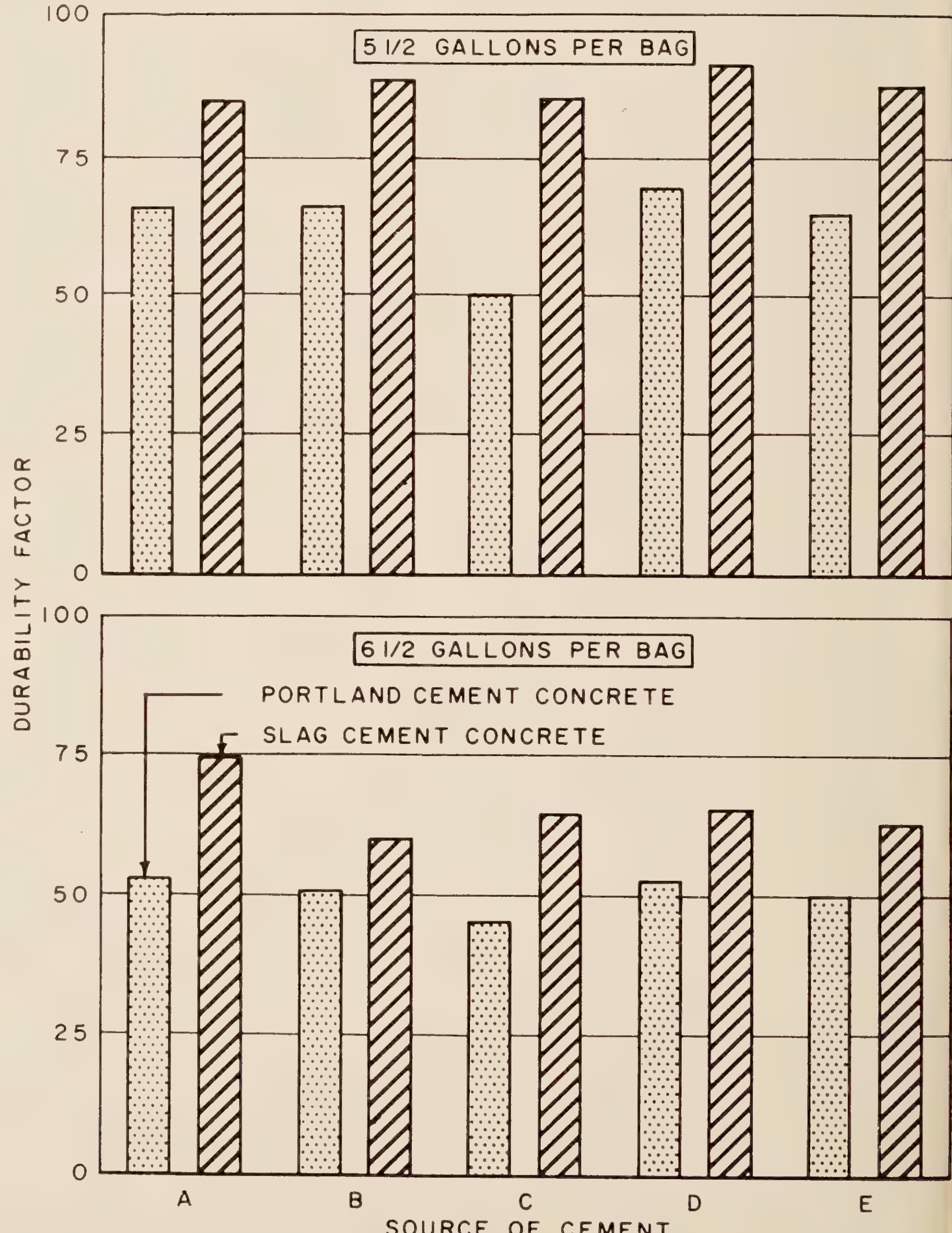

Figure 5.—Durability factors derived from freezing and thawing tests for portland and slag cement concretes.

Table 12.—Resistance of concrete to scaling[1]

Cement		Rating[2] after freezing and thawing with calcium chloride for indicated cycles								
		5½ gallons per bag of cement			6½ gallons per bag of cement			7½ gallons per bag of cement		
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	9
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

1 Specimens were 16- by 20- by 4-inch slabs, stored in moist air 28 days prior to placing in exposure area. Each value is an average of 2 tests. Air content approximately 5½ percent.
2 Rating of 0 indicates no scaling and 10 indicates deep scaling over entire surface.

Table 13.—Mortar bar expansion test results[1]

Cement				Expansion of 1- by 1- by 10-inch mortar bars, expressed in percent																	
				ASTM Method C 227–52 T			Federal SS–C–208B			Modified test: 0 percent opal			Modified test: 0.5 percent opal			Modified test: 1.0 percent opal			Modified test: 2.0 percent opal		
Source	Type	Slag[2]	Alkali[3]	8 wk.	6 mo.	1 yr.	8 wk.	6 mo.	1 yr.	8 wk.	6 mo.	1 yr.	8 wk.	6 mo.	1 yr.	8 wk.	6 mo.	1 yr.	8 wk.	6 mo.	1 yr.
A	I	--	0.32	0.12	0.19	0.20	0.02	0.05	0.03	0.02	0.02	0.02	0.12	0.28	0.35	0.17	0.33	0.56	0.07	0.10	0.13
A	IS	45	.37	.00	.00	.00	.00	.00	.01	.01	.01	.02	.02	.03	.03	.03	.08	.12	.04	.04	.07
B	I	--	.19	.02	.14	.16	.03	.07	.10	.03	.03	.04	.02	.06	.12	.03	.06	.06	.02	.03	.04
B	IS	45	.22	.00	.00	.01	.00	.00	.00	.02	.02	.02	.02	.03	.03	.01	.02	.03	.02	.02	.03
C	I	--	.32	.14	.23	.24	.10	.10	.14	.01	.02	.02	.05	.11	.18	.07	.16	.35	.04	.08	.10
C	IS	25	.61	.02	.07	.11	.00	.01	.02	.00	.01	.02	.18	.27	.27	.24	.40	.45	.16	.24	.32
D	I	--	.21	.00	.05	.10	.01	.02	.03	.01	.01	.02	.01	.02	.07	.00	.01	.02	.01	.01	.02
D	IS	40	.22	.00	.00	.00	.00	.00	.00	.02	.01	.01	.02	.01	.02	.02	.01	.01	.01	.01	.01
E	I	--	.82	.20	.26	.22	.16	.13	.16	.02	.02	.02	.12	.14	.14	.26	.29	.30	.38	.55	.57
E	IS	35	.75	.05	.06	.07	.04	.04	.04	.01	.01	.02	.08	.11	.11	.14	.26	.28	.10	.20	.26

1 Tests were made at 8 weeks, 6 months, and 1 year. Each value is average of tests on 4 or 6 beams.
2 Percent of slag used in manufacturing type IS cement.
3 Equivalent alkalies as Na_2O (see table 1).

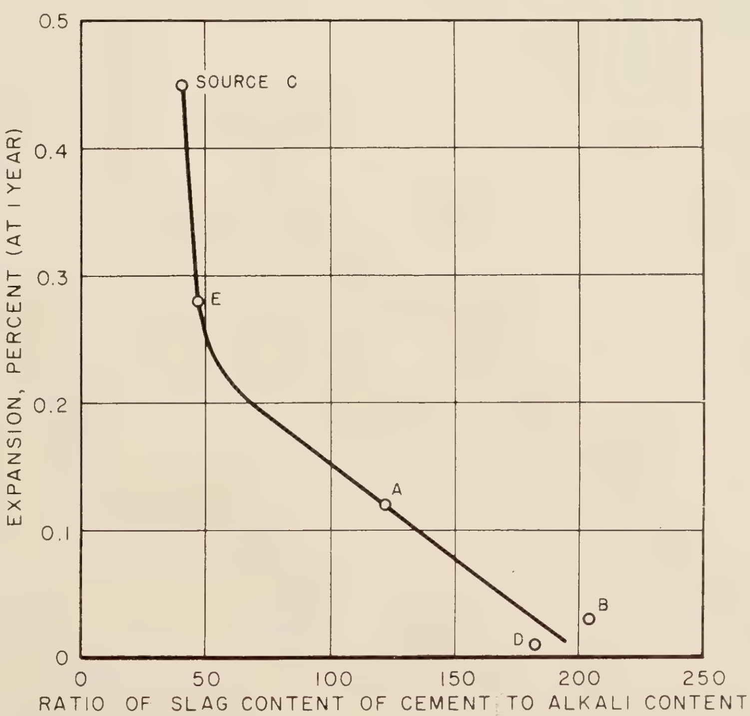

Figure 6.—Effect of slag content and alkali content of slag cements on expansion of mortar bars containing 1 percent of alkali-reactive opal (ratios expressed as percentages).

New Publications

Manual on Uniform Traffic Control Devices

The Bureau of Public Roads has just published the newly revised *Manual on Uniform Traffic Control Devices for Streets and Highways.* The new standards, updated from 1948, were drafted by the National Joint Committee on Uniform Traffic Control Devices, and approved by the Committee's member organizations, the American Association of State Highway Officials, the Institute of Traffic Engineers, the National Committee on Uniform Traffic Laws and Ordinances, the American Municipal Association, and the National Association of County Officials. The latter two organizations joined the National Joint Committee during the past year and are expected to impart added impetus to the modernization of traffic control devices throughout the nation.

The Bureau of Public Roads actively assisted the National Joint Committee in its work, and has a responsible interest in seeing that the results are broadly applied. By existing Federal highway legislation the signs, signals, and markings installed on highways constructed with Federal-aid funds are subject to approval by the State highway department with concurrence of the Federal Highway Administrator, who is directed to concur only in installations that promote safe, efficient highway use.

This new edition is expected to lend valuable service towards the safe and efficient use of the new highways being constructed in the Federal-aid program, as well as of the older streets and highways.

First published in 1935, and periodically reviewed and revised, the Manual reflects widely accepted and time-tested traffic control practices in the design and application of control devices, as well as extensive research into the principles of safe and orderly movement of vehicles and pedestrians. The newest edition includes, for the first time, specific standards for expressway signing, a major section on signing and marking for construction and maintenance operations, and a brief treatment of civil defense signing.

A significant feature of the new Manual is its elimination of certain alternatives in traffic control devices that previously were permitted, and the substitutions of a single standard. A notable example of this is the stripe to mark no-passing zones. In the future, according to the Manual, all such zones are to be marked with a yellow line to the right of the center stripe.

Another innovation is that, in general, the sizes of the newly specified traffic signs will be larger than those now in use, to provide greater visibility, particularly on multilane highways where driving is at higher speeds. Freeways and expressways in particular are to have larger and higher signs, and in specified places they will be placed overhead.

The *Manual on Uniform Traffic Control Devices for Streets and Highways* may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., at $2 per copy.

Peak Rates of Runoff From Small Watersheds

Peak Rates of Runoff From Small Watersheds, published in April 1961, is No. 2 of the Bureau of Public Roads hydraulic design series. It reports a research study of peak rates of runoff from small watersheds, and presents a procedure for the practical application of the results of that study. The study was limited to watersheds with areas of 25 square miles or less, located east of the 105th meridian.

In parts I and II of the publication, statistical analyses of data from samples of gaged and ungaged watersheds demonstrate that there is a correlation between a topographic index, a precipitation index, and the watershed area; and a correction coefficient is developed for use when the topographic index indicates differences in drainage characteristics of the watersheds.

Parts III and IV present a practical procedure for application of the research results, and include a discussion of some of the considerations that must be taken into account in its use. The process, described step by step, involves the use of lithological and rainfall index maps and a series of correlation nomographs.

Peak Rates of Runoff From Small Watersheds is available from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., at 30 cents per copy.

U.S. GOVERNMENT PRINTING OFFICE: 1961

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A list of the more important articles in PUBLIC ROADS *and title sheets for volumes 24–30 are available upon request addressed to Bureau of Public Roads, Washington 25, D.C.*

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