

FINAL REPORT

EVALUATION OF HYDRAULIC CEMENT CONCRETES  
CONTAINING SLAG ADDED AT THE MIXER

by

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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## ABSTRACT

The study evaluated the effect of ground, granulated, iron blast-furnace slags on the properties of hydraulic cement concretes such as normally used in highway construction. Two cements with different alkali contents and two slags with different activity indices, 100 and 120, were used. Slags were used as replacements for portions of portland cement at 40%, 50%, and 65% by weight. This final report presents data on the properties of the freshly mixed concrete and the test results on time of set, heat of hydration, compressive strength, flexural strength, permeability, resistance to freezing and thawing, length change values, and the results of petrographic examinations including data on air voids, carbonation, and hydration.

The test results for the laboratory specimens indicate that mixtures with the slags exhibit delay in set and slower development of compressive strength at early ages than do conventional mixtures, but have equal or better strengths at later ages. The incorporation of slag reduces the permeability of concrete considerably.

It is concluded from this study that concretes in which up to 50% by weight of the cement has been replaced with a slag meeting the requirements of ASTM C989 and having a minimum activity index of 100 are satisfactory for use in highway construction.

To Convert From	To	Multiply By
<b>Length:</b>		
in-----	cm-----	2.54
in-----	m-----	0.025 4
ft-----	m-----	0.304 8
yd-----	m-----	0.914 4
mi-----	km-----	1 . 609 344
<b>Area:</b>		
in <sup>2</sup> -----	cm <sup>2</sup> -----	6.451 600 E+00
ft <sup>2</sup> -----	m <sup>2</sup> -----	9.290 304 E-02
yd <sup>2</sup> -----	m <sup>2</sup> -----	8.361 274 E-01
mi <sup>2</sup> -----	Hectares-----	2.589 988 E+02
acre (a)-----	Hectares-----	4.046 856 E-01
<b>Volume:</b>		
oz-----	m <sup>3</sup> -----	2.957 353 E-05
pt-----	m <sup>3</sup> -----	4.731 765 E-04
qt-----	m <sup>3</sup> -----	9.463 529 E-04
gal-----	m <sup>3</sup> -----	3.785 412 E-03
in <sup>3</sup> -----	m <sup>3</sup> -----	1.638 706 E-05
ft <sup>3</sup> -----	m <sup>3</sup> -----	2.831 685 E-02
yd <sup>3</sup> -----	m <sup>3</sup> -----	7.645 549 E-01

NOTE: 1m<sup>3</sup> = 1,000 L

<b>Volume per Unit Time:</b>		
ft <sup>3</sup> /min-----	m <sup>3</sup> /sec-----	4.719 474 E-04
ft <sup>3</sup> /s-----	m <sup>3</sup> /sec-----	2.831 685 E-02
in <sup>3</sup> /min-----	m <sup>3</sup> /sec-----	2.731 177 E-07
yd <sup>3</sup> /min-----	m <sup>3</sup> /sec-----	1.274 258 E-02
gal/min-----	m <sup>3</sup> /sec-----	6.309 020 E-05
<b>Mass:</b>		
oz-----	kg-----	2.834 952 E-02
dwt-----	kg-----	1.555 174 E-03
lb-----	kg-----	4.535 924 E-01
ton (2000 lb)-----	kg-----	9.071 847 E+02
<b>Mass per Unit Volume:</b>		
lb/yd <sup>2</sup> -----	kg/m <sup>2</sup> -----	4.394 185 E+01
lb/in <sup>3</sup> -----	kg/m <sup>3</sup> -----	2.767 990 E+04
lb/ft <sup>3</sup> -----	kg/m <sup>3</sup> -----	1.601 846 E+01
lb/yd <sup>3</sup> -----	kg/m <sup>3</sup> -----	5.932 764 E-01
<b>Velocity: (Includes Speed)</b>		
ft/s-----	m/s-----	3.048 000 E-01
mi/h-----	m/s-----	4.470 400 E-01
knot-----	m/s-----	5.144 444 E-01
mi/h-----	km/h-----	1.609 344 E+00
<b>Force Per Unit Area:</b>		
lbf/in <sup>2</sup> -----	Pa-----	6.894 757 E+03
lbf/ft <sup>2</sup> -----	Pa-----	4.788 026 E+01
<b>Viscosity:</b>		
cS-----	m <sup>2</sup> /s-----	1.000 000 E-06
P t-----	Pa's-----	1.000 000 E-01

Temperature: °F-32) <sup>5</sup>/9 = °C

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BACKGROUND

Iron blast-furnace slag is a nonmetallic product consisting essentially of silicates and aluminosilicates of calcium that is developed in a molten condition simultaneously with iron in a blast furnace.(1) When the molten slag is rapidly chilled, usually by quenching with water, a glassy, granular material called "granulated, iron blast-furnace slag" is formed. When ground, this material is suitable for use as a replacement for a portion of the portland cement normally used in concrete.(2) Slag with a suitable activator, that is either present in the slag or contributed by other ingredients of the concrete mixture, develops hydration products similar to those of portland cement. The presence and the source of the activators will determine if a slag is pozzolanic, cementitious, or both.

The first use of granulated slag in portland cement was in Germany in 1892.(3) However, the utilization of slag as a cementitious material dates at least from 1774, when Lorient made a mortar using blast-furnace slag and slaked lime.(4)

Slag can be used as a raw material in the manufacture of portland cement or as a cementitious material in concrete, if combined in ground form with hydrated lime or portland cement.(5) Historically, slag cements were produced by intergrinding granulated slag with portland cement clinker and were sold as blended cements. However, the use of slag as a separate cementitious material added at the concrete mixer is now being promoted. This approach provides a greater flexibility in the proportioning of concrete mixtures and results in some manufacturing advantages related to the efficiency of grinding. Use of slag in this manner is gaining acceptance in South Africa, North America, Japan, the United Kingdom, and Australia. ASTM has recently published a specification, C989-82, that defines the requirements of ground iron blast-furnace slag for use in concrete and mortars.(1)

The use of quality slag as a partial replacement for portland cement at optimum proportions could improve the quality of concrete without increasing the cost, or it could provide mixtures equal in quality to regular mixtures containing portland cement only as the cementitious material at a reduced cost.(2) It is claimed that slag in concrete will improve workability; reduce permeability, segregation, bleeding and heat of hydration; increase resistance to sulfate and alkali-aggregate reactions; and increase the ultimate strength over that attained by similar concrete utilizing only portland cement as the cementitious material.(2,6) There are also possible disadvantages resulting from the use of slags. Strength development at early ages is slower for mixtures containing slag as compared to mixtures without slag.(6) Also, the strength development of mixtures with slag is more adversely influenced by cold weather than are mixtures without slag. There is also limited knowledge on the effects of slag on (1) air entrainment and, therefore, freeze-thaw durability, especially in the presence of deicers, (2) the nature of the carbonated surface, which may affect resistance to scaling and flaking, and (3) drying shrinkage.

Besides the possible beneficial effects on the properties of concrete, the use of slag would also provide energy conservation since the production of ground, granulated slag has been stated to use only one-fifth the energy required to produce portland cement,(2) and would utilize by-products from manufacturing activities, both of which are consistent with national goals. This study evaluated the effect of slags on some properties of concrete.

#### OBJECTIVES

The objectives of the study were as follows:

1. To obtain a quantitative evaluation of the effect of ground, granulated slags on the properties of concrete such as normally used in highway construction. Properties compared were time of set, heat of hydration, compressive strength, flexural strength, permeability, resistance to freezing and thawing, air void system, length change, nature of carbonation, and hydration reactions.
2. To establish a suitable nonproprietary specification for slag. This entailed evaluating ASTM specification C989 for use by the Virginia Department of Highways & Transportation.

#### SCOPE

Cements and slags, each from two sources and the latter in a form that can be added at the mixer, were used in 40 batches of concrete

using 20 material combinations as summarized in Table 1. This report presents the data on the properties of the freshly mixed concrete and the test results on time of set, heat of hydration, compressive strength, flexural strength, permeability, resistance to freezing and thawing, length change values, and the results of petrographic examinations, including data on air voids, carbonation, and hydration.

Table 1

## Combination of Materials and Code Designations

<u>Code Designations</u>	<u>Cement<sup>a</sup></u>	<u>Slag<sup>b</sup></u>	<u>% Replacement</u>	<u>Water Reducer</u>
C1	1	--	--	--
C1S1-40	1	1	40	--
C1S1-50	1	1	50	--
C1S1-65	1	1	65	--
C1S2-40	1	2	40	--
C1S2-50	1	2	50	--
C1S2-65	1	2	65	--
C2	2	--	--	--
C2S1-40	2	1	40	--
C2S1-50	2	1	50	--
C2S1-65	2	1	65	--
C2S2-40	2	2	40	--
C2S2-50	2	2	50	--
C2S2-65	2	2	65	--
C1R	1	--	--	Yes
C1S1-50R	1	1	50	Yes
C1S2-50R	1	2	50	Yes
C2R	2	--	--	Yes
C2S1-50R	2	1	50	Yes
C2S2-50R	2	2	50	Yes

<sup>a</sup>Cement 1 was low alkali Type I-II, cement 2 was high alkali Type I.

<sup>b</sup>Slag 1 had higher activity index.

## MATERIALS

One of the two cements, C1, was Type I-II with a total alkali content of 0.49% expressed as equivalent sodium oxide ( $\text{Na}_2\text{O}$ ) and the other, C2, was Type I with 0.68% total alkalis. The chemical and physical analyses of the cements are shown in Table A-1 in the Appendix.

Two slags with different slag activity indices meeting the requirements of ASTM C989 were used. The first slag, S1, was furnished to meet the index of 120% and the other, S2, to meet 100%. The physical and chemical analyses of the slags are given in Table A-2. In the laboratory, mortar batches were prepared to determine the indices of the slags, using the cement with the higher alkali content, C2, which meets the requirements of ASTM C989 for the slag activity test. At 28 days the index for S1 was determined as 130% and that for S2 as 101% when 9 cubes prepared from 3 batches for each of the reference cements and the two slags were tested.

The fine aggregate was a siliceous sand with a specific gravity of 2.59 and a fineness modulus of 2.90. The coarse aggregate was crushed granite gneiss with a specific gravity of 2.78 and a dry rodded unit weight of 103.1 lb/ft<sup>3</sup>. The nominal maximum aggregate size was 1 in. All the batches contained a commercially available vinsol resin for air entrainment. The amount of the admixture was varied to obtain the desired air contents. The water reducer used in some of the batches was a commercially available hydroxylated polymer. The average dosage recommended by the producer was used.

## MIXTURE PROPORTIONS AND PREPARATION

The mixtures were proportioned in accordance with ACI 211.1. All the mixtures without the water reducer were prepared to meet the requirements for A3 general use concrete of the Virginia Department of Highways and Transportation shown in Appendix Table A-3, except that in the experimental batches slags at 40%, 50%, and 65%, by weight, were used to replace equal portions of the portland cement. The cementitious material (cement plus slag) content was 588 lb/yd<sup>3</sup> and the ratio of water to cementitious material was 0.48, which is slightly below the allowable value of 0.49. The minimum 28-day compressive strength of A3 concretes is 3,000 lbf/in<sup>2</sup>.

The mixtures with the water reducer were proportioned to meet the new A4 bridge deck concrete requirements of the Department as given in Table A-3, and contained 635 lb/yd<sup>3</sup> of cementitious material, either portland cement as in the controls or 50% replacement of the cement with slag by weight of cement. The minimum 28-day compressive strength of this concrete was 4,500 lbf/in<sup>2</sup> and a maximum ratio of water to cementitious material of 0.45 was used in all these mixtures.

The ingredients for each material combination shown in Table 1 were mixed in a pan-type mixer following the procedures of ASTM C192. The slags were added after the cement and then the water reducer was added following introduction of the air entraining admixture and both were dispersed in some of the mixing water. For each material combination, the batches were duplicated for assurance and the two sets were prepared on different days.

## TESTING AND RESULTS

The freshly mixed concretes were tested for air content, slump, and unit weight. Samples were prepared for the time of set, heat of hydration, compressive and flexural strengths, permeability, resistance to freezing and thawing, length change, and petrographic examination to obtain data on air voids, carbonation, and hydration. The sample preparation, testing, and the results are discussed below.

### Characteristics of Freshly Mixed Concrete

The air contents were measured using the pressure method, ASTM C231, slumps by ASTM C143, and unit weights by ASTM C138. The results, reported as an average of two batches, are summarized in Table A-4 of the Appendix. Workable concretes were achieved and standard specification requirements were met, except that for two material combinations with water reducers slumps were slightly higher than required. The air contents of the individual batches ranged between 6.1% and 8.0%. The narrow range was desired for a close comparison of the properties, especially the comparisons of the strength and the level of resistance to freezing and thawing, between the control and the experimental mixtures.

### Time of Set

The time of set was determined in accordance with ASTM C403 on 4 material combinations that contained C1 and S1. For each material combination, two mortar specimens, one from each batch, were tested. The times of initial and final sets were determined from the specified penetration resistance and are summarized in Table 2. The results indicate that the addition of slag delayed the initial set up to about 1 hour and the final set up to 2 hours.

Table 2

Time of Set

<u>Material Combination</u>	<u>Initial Set</u>	<u>Final Set</u>
C1	5:32	7:17
C1S1-40	6:40	8:50
C1S1-50	6:13	8:49
C1S1-65	6:38	9:08

Heat of Hydration

The early temperature rise during hydration in concretes for some of the material combinations shown in Table 3 was determined by following a test procedure of the Corps of Engineers, CRD-C 38-73. A cylinder measuring 6 x 12 in was prepared from each batch and placed in well-insulated autogeneous curing containers to simulate adiabatic conditions. A thermocouple was inserted at the center of the cylinder and the temperature was recorded for 48 hours at one-hour intervals and plotted on graph paper. The temperatures attained at certain ages and the maximum temperature reached are summarized in Table 3. The results indicate that the rate of temperature rise at early ages was lower for the experimental mixtures, and the maximum temperature reached was also lower. At a later age, the temperature of the control dropped at a faster rate than that of the experimental mixtures. At 48 hours, the temperatures recorded for the experimental mixtures were, in general, higher than those for the controls.

Compressive Strength

The compressive strengths of concretes for all the material combinations were determined in accordance with AASHTO Test Method T23. Moist cured cylinders measuring 4 x 8 in were capped with sulfur-mortar and tested at 14, 28, and 56 days. Some of the A3 concretes were also tested at 7 days, as shown in Table 4. Each strength value for a certain age is an average of 4 cylinders, two from each of the duplicate batches.

Table 3

Temperature Rise as Percent of Control  
(Average of 2 Specimens)

<u>Material Combination</u>	<u>Time, Hours</u>						<u>Max.</u>
	<u>5</u>	<u>10</u>	<u>15</u>	<u>25</u>	<u>35</u>	<u>48</u>	
C1	100 (83) <sup>a</sup>	100 (118)	100 (129)	100 (130)	100 (122)	100 (111)	100 (132)
C1S1-40	93	81	83	91	98	103	91
C1S1-50	96	82	81	89	97	103	89
C1S1-65	95	78	77	84	94	101	87
C1S2-50	98	77	78	82	89	96	82
C1R	100 (80)	100 (100)	100 (137)	100 (140)	100 (129)	100 (116)	100 (142)
C1S1-50R	96	83	73	85	98	105	92
C1S2-50R	96	80	72	79	91	102	87

<sup>a</sup>Numbers in parentheses are the values in °F.

Table 4  
Strength Data as Percent of Control  
(Average of 4 Specimens)

Material Combination	Compressive Strength				Flex. Str. 28 days
	7 days	14 days	28 days	56 days	
C1	100 (3,680) <sup>a</sup>	100 (4,400)	100 (4,850)	100 (5,315)	100 (684)
C1S1-40	83	95	106 <sup>b</sup>	110	101
C1S1-50	84	100	100 <sup>b</sup>	104	99
C1S1-65		c	104	97	109
C1S2-40		88	101	102	104
C1S2-50		101	110	110	108
C1S2-65		85	94	91	93
C2	100 (3,890)	100 (4,430)	100 (4,610)	100 (5,210)	100 (663)
C2S1-40	92	106	100	103	106
C2S1-50	89	92	101	101	103
C2S1-65	90	100	108	96	101
C2S2-40		92	102	101	109
C2S2-50		87	97	94	109
C2S2-65		87	93	94	91
C1R		100 (5,540)	100 (5,860)	100 (6,130)	100 <sup>d</sup> (644)
C1S1-50R		97	107	114	110
C1S2-50R		89	100	100	106
C2R		100 (5,580)	100 (5,930)	100 (6,120)	100 (664)
C2S1-50R		94 <sup>d</sup>	104	112	105
C2S2-50R		92	102	105	103

<sup>a</sup>Numbers in parentheses are the values in lbf/in<sup>2</sup>.

<sup>b</sup>Average of 2 specimens.

<sup>c</sup>No specimens because of limited batch size.

<sup>d</sup>Average of 3 specimens.

The results indicate that all the mixtures achieved satisfactory strength levels. However, the 7-day compressive strengths of mixtures containing slag were lower than those of the controls. The maximum difference was 17% for one set of specimens. At 28 days and 56 days, about equal or better strengths were obtained for 40% and 50% replacements in all of the mixtures except the combination of high alkali cement with the lower activity index slag at the 50% replacement. The 65% replacements, used only in A3 mixtures, showed lower strengths at 56 days.

The mixtures containing high alkali cement, C2, showed lower differences in strengths at 7 days but the 56 day strength values were, in general, about equal to or lower than those for the mixtures with the cement having a lower alkali content. Mixtures containing the slag with the higher activity index achieved a higher rate of strength development at early ages and the 56-day strengths were about equal to or better than those of the mixtures with the slag having a lower activity index.

#### Flexural Strength

The flexural strengths for all the material combinations were determined in accordance with ASTM C78 using simple beams with third-point loading. The test beams measured 3 x 3 x 11½ in and were tested at 28 days. The flexural strength values are shown as an average of 4 specimens from two batches in Table 4. The results indicate that the flexural strength values of mixtures using slag were about equal to or better than those of the controls, except that the mixture with the slag with the lower activity index gave somewhat lower strengths at the 65% replacement.

#### Permeability

The permeability to chloride ions of some of the concretes shown in Table 5 were determined using AASHTO Test Method T277-83I, which was initially described in an FHWA report.(7) It involves the application of 60 volts d.c. for 6 hours to a concrete specimen that is vacuum saturated. The total charge, expressed in coulombs, that passes through the specimen during the 6-hour period is related to chloride permeability. The test specimens were 2 in thick and 4 in in diameter and were cut from the top of standard 4 x 8 in cylinders. The cylinders were moist cured for 2 weeks and air dried for 6 weeks prior to being tested.

Table 5  
Permeability Data  
(Average of 4 Specimens)

<u>Material Combination</u>	<u>Charge Passed (Coulombs)</u>	<u>% Control</u>
C1	8,580	100
C1S1-40	5,330	62
C1S1-50	3,560	41
C1S1-65	2,800	33
C1S2-50	3,260	38
C2	6,660	100
C2S1-50	3,200	48
C2S2-50	2,950	44
C2R	8,570	100
C2S1-50R	4,140	48
C2S2-50R	3,470	40

The results, expressed as an average of 4 specimens from two batches, are summarized in Table 5 and indicate that the incorporation of slag into the mixtures considerably reduced the permeability. The decrease in permeability was proportional to the amount of cement replacement; the higher the slag content, the less the permeability. In the experimental mixtures at 50% replacement, the charge passing through the specimens ranged from 38% to 48% of that of the controls. In the A3 mixtures at 65% replacement, it was 33%. It is noted that the coulomb values for the specimens with 40% replacement and those for 50% replacement with C2, S1, and the water reducer, although considerably reduced from those of the controls, were in excess of 4,000, which is reported to be an indication of high permeability.(7) It is also noted that the mixtures with the slag having the lower activity index had lower coulomb values and thus lower permeability than similar mixtures with the slag having the higher activity index. However, the significance of these differences cannot be evaluated from the available data.

#### Resistance to Freezing and Thawing

The resistance of some of the material combinations shown in Table 6 were determined using ASTM C666 Procedure A with two modifications. One was in the curing of the specimens and the other in the addition of 2% NaCl to the test water. The ASTM test procedure requires

moist curing for 2 weeks, unless some other age is specified. At the Research Council the specimens are dried 1 week in addition to the 2 weeks in moist curing. This type of curing is denoted as regular in Table 6, and is believed to be representative of the environment to which highway structures and pavements are exposed. In addition, two other types of curing were used. In one of these, shown as CC in Table 6, a white pigmented curing compound was applied to the top surface of the specimens as the water sheen was disappearing and then the molded sides of the beam were coated with the curing compound immediately after removal from the molds at 1 day. The beams were air cured, and at an age of 1 week were put in the moist room for a week and then air dried for an additional week before testing. Thus, the total curing period was 3 weeks. The other curing, indicated by LC in Table 6, was similar to CC, except that the top surface was treated with a saturated lime water solution as the sheen was disappearing, and the curing compound was added as the lime water solution dried on the surface. The varied curing conditions were included to observe if they had an effect on surface scaling when the specimens were subjected to cycles of freezing and thawing. Parallel studies of these curing conditions will be found in the section on petrographic studies.

Under the modified test procedure denoted as regular in Table 6, which includes 2 weeks of moist curing, 1 week of air drying, and 2% NaCl in the test water, acceptable performance by Council standards requires that at 300 cycles the average weight loss be 7% or less, the durability factor be 60 or more, and the surface rating be 3% or less. The surface rating was determined by estimating the proportion of the surface having ratings as given in ASTM C672 and the top surface was rated separately from the molded surfaces. The final rating for each beam was calculated by averaging the weighted ratings computed for the top and the molded surfaces separately.

The results at 300 cycles, summarized in Table 6, for weight loss, durability factor (DF), and surface rating indicate that all the concretes with and without the slag exhibited satisfactory performance. The weight loss values generally indicated that mixtures containing slags exhibited higher surface ratings. An exception was in the A4 mixtures containing slag with the higher activity index, which had a weight loss equal to that of the control. The surface scaling increased with the increase in the amount of cement replaced by the slag. However, all the durability factors were very high, indicating sound internal structures, at the end of 300 cycles of freezing and thawing. The surface rating values, also indicative of surface scaling, were in agreement with the weight loss values.

Table 6

Freeze-thaw Data at 300 Cycles  
(Average of 4 Specimens)

<u>Material Combination</u>	<u>Curing</u>	<u>Wt. Loss</u>	<u>D F</u>	<u>Surface Rating</u>
C1	Reg	2.1	101	1.2
C1S1-40	Reg	2.9	101	1.3
C1S1-50	Reg	3.2	98	1.4
C1S1-65	Reg	2.9	100	1.6
C1S1-65	CC	5.2	99	1.9
C1S1-65	LC	5.4	97	2.0
C1S2-40	Reg	2.9	95	1.5
C1S2-50	Reg	4.0	96	1.6
C1S2-65	Reg	5.1	98	1.8
C1S2-65	CC	9.1	92	2.5
C1S2-65	LC	9.9	88	2.8
C2	Reg	1.9	98	1.2
C2	LC	3.7	96	1.5
C2S1-65	Reg	4.1	99	1.6
C2S1-65	CC	6.4	97	1.8
C2S1-65	LC	5.8	98	1.7
C2S2-65	Reg	5.1	99	1.8
S2S2-65	CC	8.1	95	2.3
C2S2-65	LC	9.6	88	2.3
C1R	Reg	1.8	98	1.1
C1R	CC	1.8	101	1.2
C1R	LC	1.3	102	1.2
C1S1-50R	Reg	1.8	96	1.1
C1S1-50R	CC	2.4	102	1.2
C1S1-50R	LC	2.8	100	1.4
C1S2-50R	Reg	3.2	97	1.6
C1S2-50R	CC	3.0	98	1.4
C1S2-50R	LC	3.5	97	1.7

Specimens cured with the curing compound, CC, and the lime and curing compound, LC, generally showed higher weight loss values in A3 mixtures compared to those cured with the regular curing. In the A4 mixtures, lower differences and mixed values were obtained. The durability factors were high and the surface ratings were in agreement with the weight loss values.

### Length Change

The length changes of some of the concretes, shown in Table 7, stored in the moist room or kept in the laboratory air were determined in accordance with ASTM C157. Two specimens measuring 3 x 3 11½ in with gage studs at both ends were prepared from each batch of concrete. When the specimens were removed from the molds, their lengths were measured, then the specimens were cured in the moist room until they reached an age of 28 days. Following this, one of the specimens was kept in the moist room for observations of expansion and the other one stored in the laboratory air for determination of the drying shrinkage. Measurements were taken at the ages specified in ASTM C157 for up to 52 weeks and the results are summarized in Table 7 for 4, 16, and 52 weeks. For the specimens cured in the moist room, the ages shown include the initial curing period of 4 weeks. For the drying shrinkage specimens, the total time of air storage was used.

Table 7

Length Change, %  
(As an Average of 2 Beams)

<u>Material Combination</u>	<u>Moist Cured</u>			<u>Air Dried</u>		
	<u>4 wk.</u>	<u>16 wk.</u>	<u>52 wk.</u>	<u>4 wk.</u>	<u>16 wk.</u>	<u>52 wk.</u>
C1	0.003	0.009	0.007	-0.036	-0.048	-0.062
C1S1-40	.006	.016	.018	- .036	- .052	- .057
C1S1-50 <sup>a</sup>	.007	.014	.020	- .037	- .052	- .062
C1S1-65	.013	.018	.018	- .035	- .057	- .069
C1S2-50	.011	.020	.022	- .035	- .054	- .064
C2 <sup>a</sup>	.007	.011	.005	- .045	- .082	- .083
C2S1-50	.006	.009	.017	- .026	- .054	- .064
C2S2-50	.013	.017	.019	- .053	- .076	- .088
C1R	.009	.007	.001	- .055	- .072	- .072
C1S1-50R	.019	.025	.028	- .034	- .046	- .051
C1S2-50R	0.026	0.036	0.035	-0.045	-0.056	-0.062

<sup>a</sup>One beam for the moist cured condition.

In general, the average expansions obtained for the mixtures with slag were more than those obtained for the control mixtures when stored in the moist room. The expansion is due to the progressive hydration of the cementitious material, and the pozzolanic materials are expected to expand slightly more.(8) The drying shrinkage values for specimens stored in the air were, in general, mixed, but the values obtained for the controls were close to those of the experimental mixtures.

### Petrographic Examinations

#### Specimens

One 3 x 4 x 16 in beam from each mix was reserved for petrographic examinations. Some of these were treated with a special curing procedure. After the beam was molded and finished and free water had disappeared, one-third of the top surface was sprayed with a saturated solution of  $\text{Ca}(\text{OH})_2$ . When the sheen again disappeared, that third and an adjacent third were again sprayed with this solution, and when the free water again disappeared the entire top surface was sprayed with a white pigmented curing compound. These curing sections are included in Figure 1. On the following day, when the beams were demolded, all of the other surfaces were sprayed with curing compound. All beams treated with curing compound were kept under ambient laboratory conditions for 1 week and then stored in the moist room for 1 week. Hydration of the beams and the carbonation of the surfaces cured by the three above described procedures were studied by thin sections prepared as shown in Figures 1 and 2, and according to the schedule in Table 8.

Hydration was studied on 4 thin sections, 2 from each duplicate batch. Carbonation was studied on 2 thin sections from only one batch because no significant differences were observed between the different mixtures. Curing was parallel with the curing of the beams tested for freeze-thaw durability.

After 1 month of moist curing the slabs for air void analysis were cut, allowed to air dry, and then lapped to provide a proper surface for linear traverse examination as in ASTM C457.

The small specimens cut for thin sections were dried by immediately placing them in acetone and, after 24 hours, vacuuming them dry. The further preparation of thin sections is fully described by Walker and Marshall.(9) Sections including the surface of the concrete were prepared by placing the surfaces facing each other to minimize the risk of loss of surface edge length during the thinning and polishing procedures.

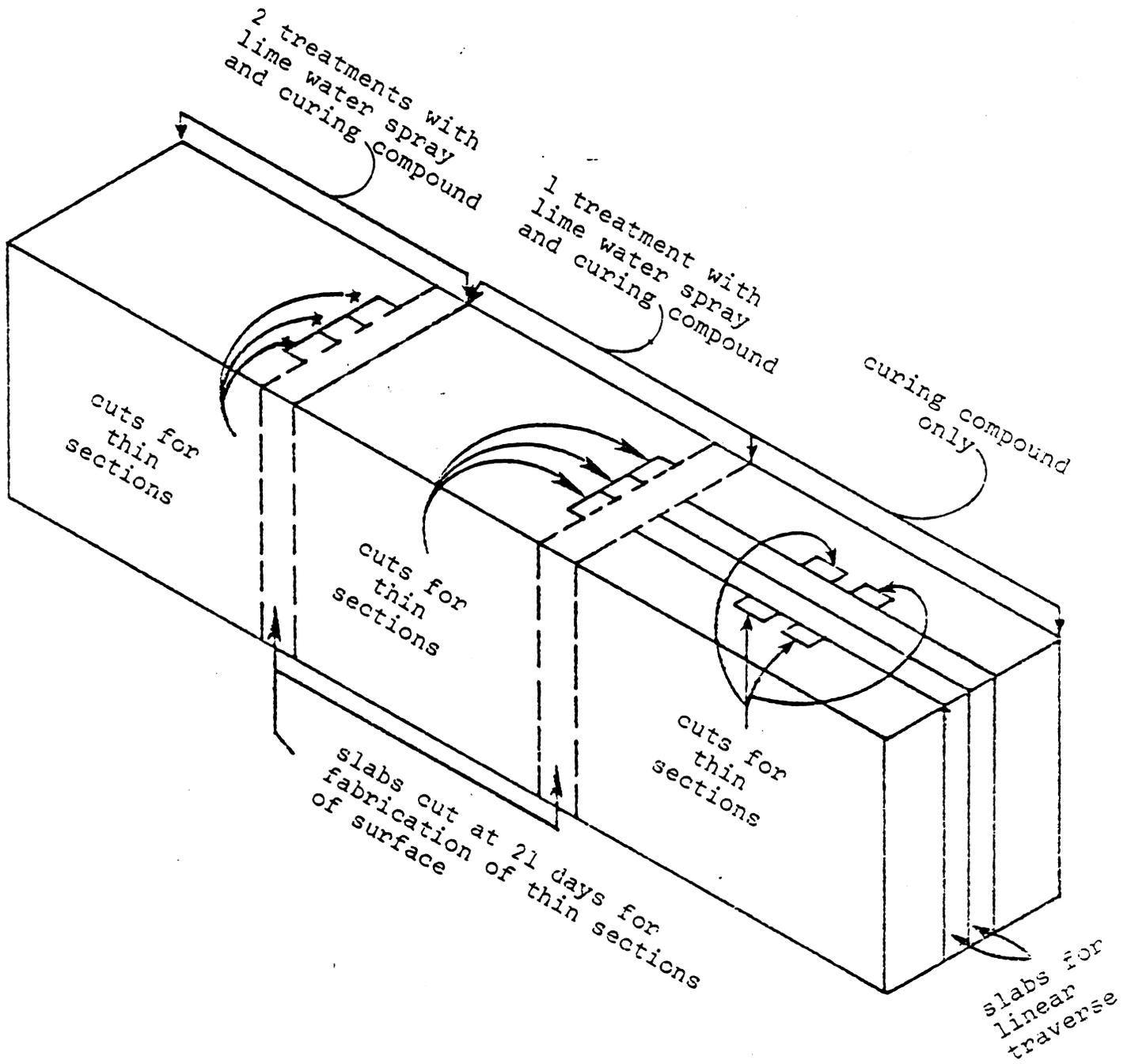
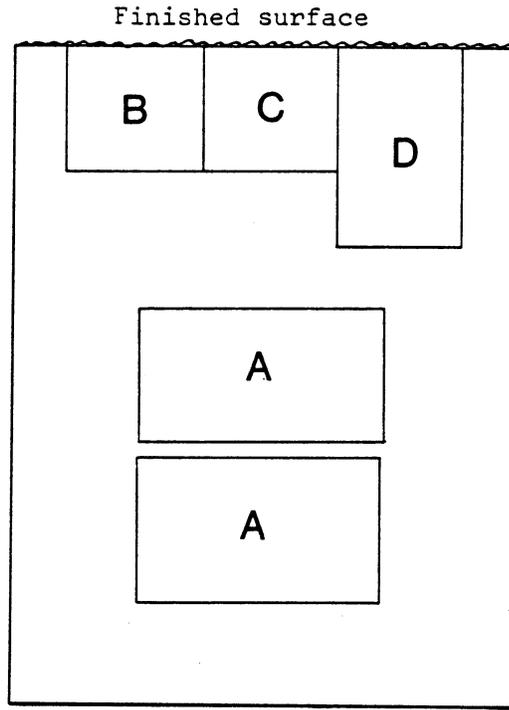


Figure 1. Cuts made in prism for petrographic studies.



Cross section of prism

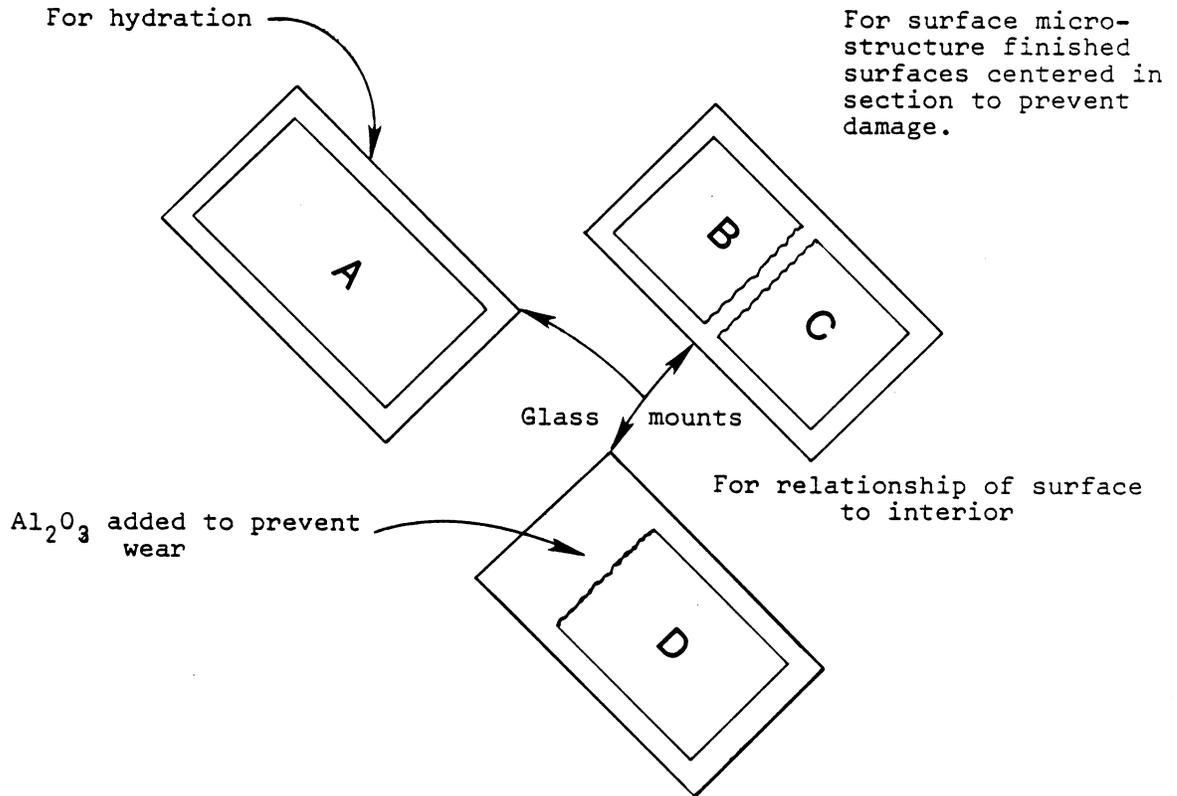


Figure 2. Location and mounting of thin sections.

Table 8

## Petrographic Examination of Thin Sections

<u>Material Combination</u>	<u>Hydration</u>	<u>Carbonation</u>
C1	a, b	c
C1S1-40	a	-
C1S1-50	a	-
C1S1-65	a	c
C1S2-65	b	c
C2	a	-
C2S1-40	a	-
C2S1-50	a	-
C2S1-65	a	c
C2S2=65	b	c
C1-R	b	c
C1S1-50R	b	c
C1S2-50R	b	c

a - At ages 14, 21, and 56 days.

b - At ages 21, 56 days, and 6 mo.

c - At 21 days on all 3 surface conditions.

Air Void System

The air void content, specific surface, and spacing factor of the air void systems of all the hardened concretes were determined using the linear traverse method of ASTM C457. The results, summarized in Table 9, indicate that for all the concretes the total void contents determined on hardened concrete were close to the upper limit of 8.0% and several exceeded this value. In general, the total void contents of hardened concrete averaged about 1% higher than the air contents obtained at the freshly mixed stage. The entrapped air voids, indicated by voids larger than 1 mm in diameter, were generally 2% or less, as is expected for adequately consolidated concretes, except that in two cases higher amounts of voids, 3.0% and 2.4% were obtained. The specific surface values were larger than 600 in<sup>-1</sup> and the spacing factor less than 0.008 in, values that are considered necessary for the protection of saturated concretes from cycles of freezing and thawing.<sup>(10)</sup> These results are consistent with the results of the freeze-thaw tests that showed satisfactory performance.

Table 9

## Air Void System of Hardened Concrete

<u>Material Combination</u>	<u>Void Content, %</u>			<u>Specific Surface, in<sup>-1</sup></u>	<u>Spacing Factor, in</u>
	<u>&gt;1 mm</u>	<u>&lt;1 mm</u>	<u>Total</u>		
C1	2.0	6.9	8.9	798	0.0038
C1S1-40	1.5	6.3	7.8	789	0.0043
C1S1-50	1.3	5.7	7.0	819	0.0047
C1S1-65	1.4	6.9	8.3	890	0.0036
C1S2-40	1.2	7.2	8.4	903	0.0034
C1S2-50	1.4	5.4	6.8	827	0.0048
C1S2-65	1.4	6.8	8.2	864	0.0037
C2	2.1	6.5	8.6	750	0.0040
C2S1-40	2.0	6.6	8.6	843	0.0036
C2S1-50	1.8	6.9	8.7	878	0.0034
C2S1-65	1.8	6.7	8.5	856	0.0036
C2S2-40	1.8	6.3	8.1	906	0.0036
C2S2-50	1.2	7.4	8.6	952	0.0034
C2S2-65	1.4	6.4	7.8	884	0.0038
C1R	3.0	7.0	10.0	675	0.0038
C1S1-50R	2.4	5.6	8.0	669	0.0050
C1S2-50R	2.0	5.7	7.7	733	0.0048
C2R	1.5	4.8	6.3	805	0.0051
C2S1-50R	1.6	6.2	7.8	834	0.0040
C2S2-50R	1.4	5.3	6.7	862	0.0046

Color

The plain concrete specimens fabricated with cement 1 were noticeably darker than those fabricated with cement 2. The former contained 1.2% more  $Fe_2O_3$  than did the latter. The concretes containing 50% and 65% slag were much less colored by the iron of the portland cement than were the plain concretes; however, the matured specimens that contained 65% slag and cement 1 and were allowed to dry thoroughly were a slightly browner shade of cream than were similar specimens containing cement 2.

The slag concrete that remained continuously moist was a dark grayish, blue green, with the color often being irregularly distributed. The streaks and patches of dark color and the contrasting cream were examined with the stereoscopic microscope and in ultrathin sections at 400x. No evidence was found to indicate that the streaks and patches were due to an uneven distribution of the slag or cement. No

differences in composition were detected; that is, there was no evidence of incomplete mixing. It has been thought that this dark grayish, blue green color is caused by minute quantities of certain sulfide minerals that exist in slag concrete only in the presence of certain pore fluids. When the slag concrete is completely dry, it becomes a uniform cream or very light brown. The color does not return when the concrete is rewetted. It is thought that the streaks and patches are due to differential drying of the pore fluids. The irregular distribution may be due to the trapping effect of aggregate particles.

### Carbonation

In ordinary portland cement concrete the carbonated surface layer is less permeable than the uncarbonated material. Pozzolans in concrete often use up the  $\text{Ca}(\text{OH})_2$  (portlandite), and thus insufficient  $\text{Ca}(\text{OH})_2$  is left to create a dense, carbonated zone. Slag-bearing concrete has been shown to have a similarly permeable carbonated surface. The various curing methods were used in an effort to produce a dense, carbonated layer on the surface of the slag concretes. As will be shown later, the slag concretes had much less  $\text{Ca}(\text{OH})_2$  than did the concretes without slag. However, the lime water cures did not produce a dense, carbonated surface. The carbonated layer of all of the specimens was so variable that no consistent differences could be detected between the slag concretes and the plain concretes, or between the various curing methods. In general, in all these concretes, including the plain concretes, the carbonated layer was deeper and more permeable than expected. This may have been caused by slow migration of  $\text{CO}_2$  through the curing compound by storage in the moist room.

### Hydration

The hydration of the slag was studied in thin sections at intervals up to 56 weeks of age. The slag particles are quite angular at early ages. They become progressively rounder and smaller and less numerous at later ages. Portland cement hydrates in slag-bearing concrete in the same manner as it does in ordinary concrete. However, there is less  $\text{Ca}(\text{OH})_2$  in slag concrete than there is in ordinary concrete.

Figures 3, 4, and 5 are photomicrographs in three types of illumination of an area of a thin section of control concrete containing cement 1 at 21 days' hydration. Figures 6, 7, and 8 are similar photomicrographs of a comparable area of concrete containing cement 1 and 65% of slag 1. The negatives and prints for Figures 4 and 7 were given the same exposure time and processing. Those for Figures 5 and 8 were also as identical as possible in exposure and processing. A comparison of Figures 4 and 7 shows how much less  $\text{Ca}(\text{OH})_2$  there was in the slag-bearing concrete, and Figures 5 and 8 show how much less permeable the slag-bearing concrete was as compared to the control.

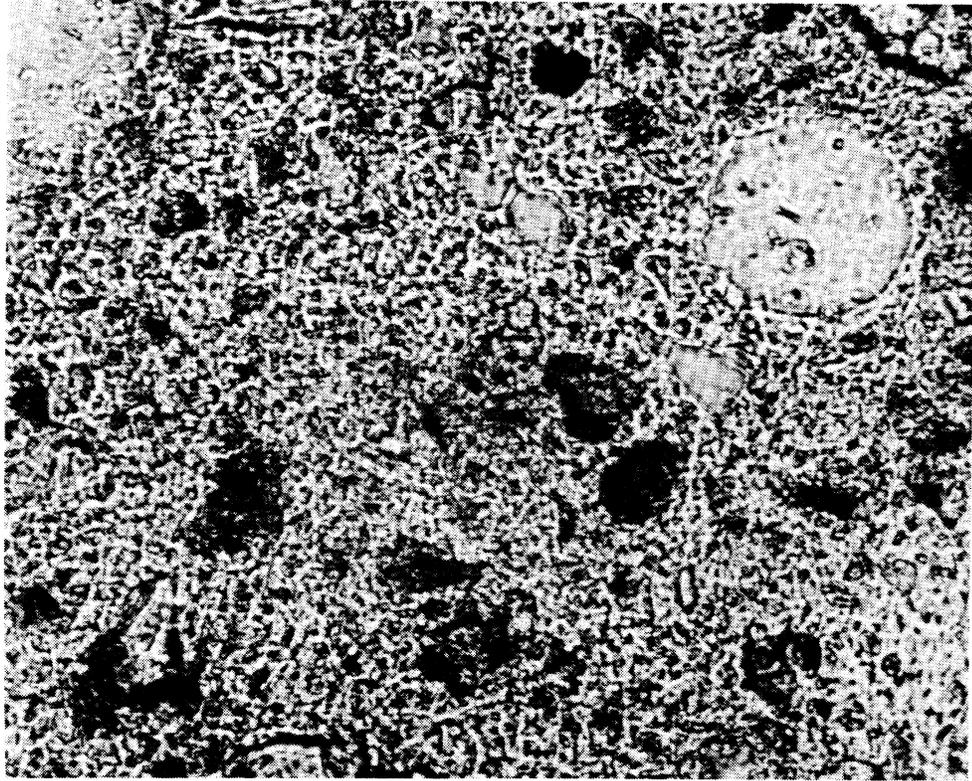


Figure 3. Control, cement 1, 400x. Plane polarized light, transmitted. Upper left a grain of quartz sand; upper right spherical air void. The dark particles are the ferrites of the cement.

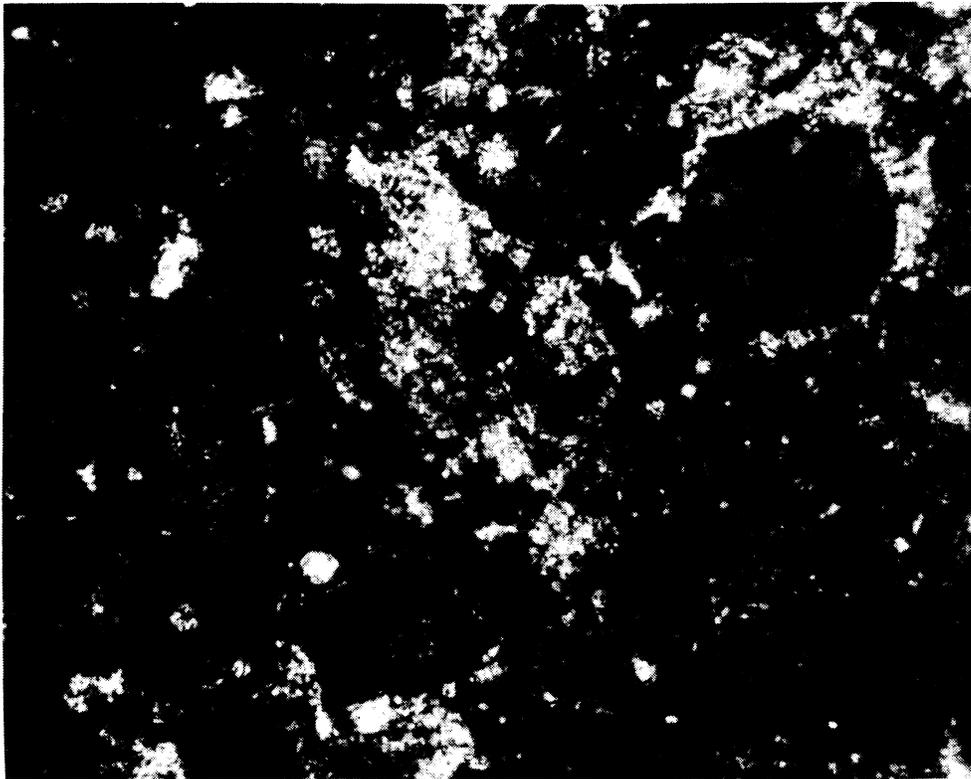


Figure 4. Same view as Figure 3. Crossed polarization plates, transmitted light. In this orientation, most of the bright areas are crystals of portlandite ( $\text{Ca}(\text{OH})_2$ ) in the cement paste. Concentrations of  $\text{Ca}(\text{OH})_2$  may be seen around the air void and scattered elsewhere.

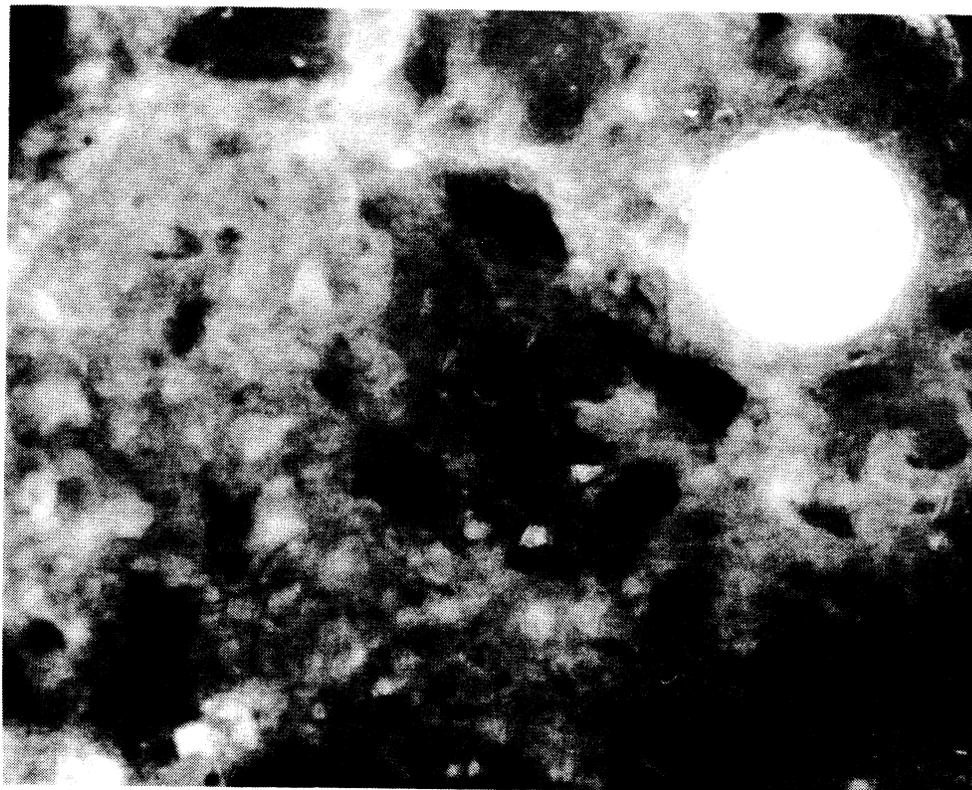


Figure 5. Same view as Figures 3 and 4. Ultraviolet light exciting the fluorescent dye in the epoxy used in the impregnation procedure. Most of the larger capillaries and all cracks and void areas are dye filled. Many of the capillaries overlap and can be focused on individually within the thickness of the section. A photograph records all the dye areas throughout the 12  $\mu\text{m}$  thickness. Many are out of focus.

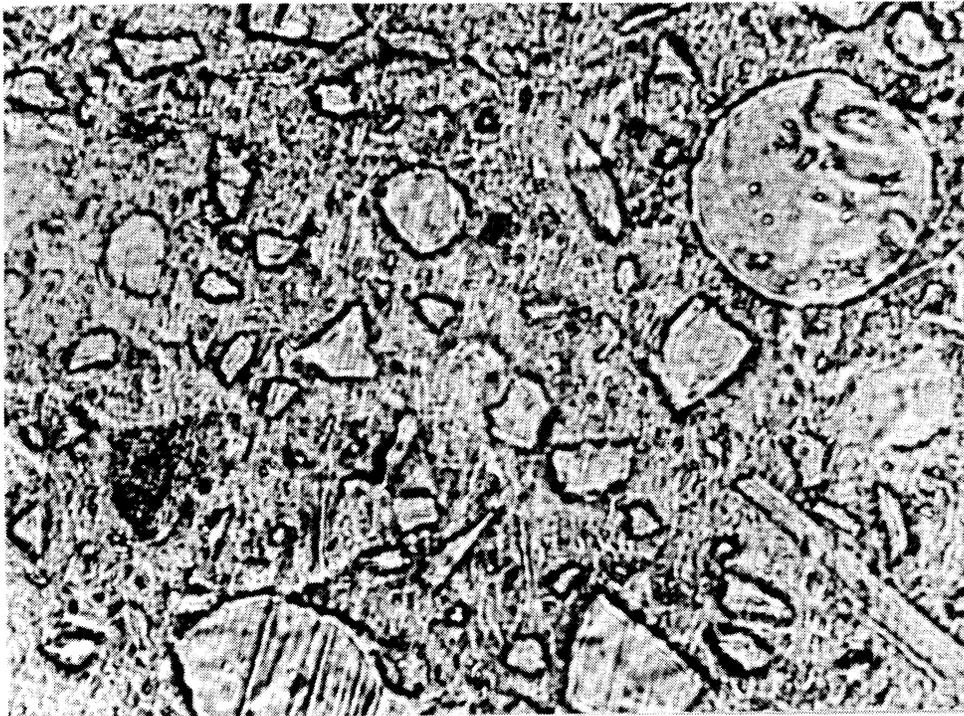


Figure 6. Slag 65% in cement 1 concrete, 400x, plane polarized light, transmitted. Upper right, a spherical air void; lower right a long, thin blade of mica aggregate. The angular fragments in the central area are slag 1 particles.



Figure 7. Same view as Figure 6. Cross polarization plates, transmitted light. Same exposure time and processing procedure as Figure 4. Aside from the mica fragment, the bright areas indicate the presence of  $\text{Ca(OH)}_2$ . It may be seen that this concrete had much less  $\text{Ca(OH)}_2$  than the control concrete.



Figure 8. Same view as Figures 6 and 7. Ultraviolet illumination. Same exposure time and processing as Figure 5. Note that the fluorescent dyed epoxy was unable to penetrate this concrete and fill capillaries to the extent shown in Figure 3. This is thought to be due mainly to the impermeability of the concrete.

Calcium hydroxide is a soluble material that can leach out and leave pores in the concrete. By the same token, ions of other substances such as chlorides can travel in solution through a concrete containing numerous crystals of  $\text{Ca(OH)}_2$  faster than through concretes less rich in  $\text{Ca(OH)}_2$ . Note the lack of calcium hydroxide in Figure 7 as compared with that in Figure 4. The rapid permeability test values shown in Table 5 indicate the low permeability of slag concretes. This is well illustrated by a comparison of Figure 5 (ordinary concrete) and Figure 8 (65% slag concrete). The fluorescent dyed epoxy permeated the ordinary concrete in Figure 5 and can be seen by illumination with ultraviolet light to have completely filled a great multitude of the large capillaries. Only a very few capillaries in Figure 8 are seen to have been filled.

In the slag concretes, the paucity of  $\text{Ca(OH)}_2$  crystals and the impermeability to epoxy were in direct relationship to the amount of slag used.

#### CONCLUSIONS

Based on the results of the tests and petrographic examinations of control mixtures and the experimental mixtures containing slags, the following conclusions are drawn.

1. The times of initial and final sets of concretes containing slag were longer than those for similar concrete containing no slag. The initial time of set was delayed up to about an hour and the final set was delayed up to 2 hours.
2. For the slag mixtures, the temperature change caused by the early hydration of the cementitious materials was at a slower rate, and lower temperatures were attained than for similar concrete without slag.
3. The mixtures containing slag exhibited slower strength development at early ages. The 7-day compressive strengths were up to 17% lower than those for the controls. However, at 28 and 56 days, equal or higher compressive strengths were obtained for concretes with slag, except for the 50% replacement with the lower activity slag, S2, and the high alkali content cement, C2, and the 65% replacements with both cements at 56 days. The percentages of the strength of the controls developed by the 50% replacement with S2 and C2 were 97% and 94%, respectively, for 28 and 56 days.
4. The mixtures containing the slag with the higher activity index had more rapid strength development at early ages than

the ones with the lower index slag. At later ages, the strengths were about equal to or higher for mixtures with the higher index slag.

5. The mixtures with the high alkali cement had a more rapid strength development at early ages. However, the long-term strengths were about equal to or lower than those of the mixtures with the low alkali cement.
6. The 28-day flexural strengths of the experimental mixtures were about equal to or higher than those of the controls, except that the slag with the lower activity index had lower strengths by as much as 9% for the 65% replacement.
7. Mixtures containing slag exhibited lower permeability to chloride ions as measured in coulombs than did mixtures without slag, the reduction being proportional to the amount of replacement. The reduction in coulombs for the 50% specimens ranged from 38% to 48% and was 33% for the only combination tested at 65% replacement.
8. The low permeability of slag concretes was demonstrated by petrographic examination of the amount of  $\text{Ca(OH)}_2$  and by examination of permeability to fluorescent dyed epoxy.
9. In general, the resistance to freezing and thawing in the presence of 2% NaCl of all the specimens with and without slag was satisfactory. However, generally higher surface scaling was observed on the mixtures with slag.
10. The linear traverse data for all the mixtures indicated the presence of a satisfactory air void system.
11. The drying shrinkage values were mixed, and comparable values were obtained for the control and experimental mixtures.
12. The streaky color distribution seen in the slag concretes was not attributable to uneven distribution of cementitious components and did not indicate lack of quality or uniform mixing, but was due to the current moisture content.
13. Hydraulic cement concrete utilizing up to 50% replacement of the portland cement with slag having an activity index of 100 or greater and meeting the requirements of ASTM C989 will provide satisfactory results in highway construction. However, attention should be given to the lower rate of strength development in early ages for form removal and the construction of superimposed elements.

## RECOMMENDATIONS

Slags with activity indices exceeding 100 and meeting the other requirements of ASTM C989 may be used as a replacement of a portion of the portland cement in hydraulic cement concrete. Concretes incorporating such slags at optimum amounts are suitable for use in highway construction. It should be recognized that mixtures with slag have an increased setting time and slower strength development at early ages, which is more adversely influenced by cold weather conditions than are the like characteristics of regular mixtures. Field use of mixtures containing slag is recommended to gain experience and to evaluate the practical significance of changes noted in the laboratory studies and possibly to observe trends not evident in the laboratory mixtures. Because of concerns for strength and freeze-thaw durability, it is recommended that at this time the activity index of the slag used be 100 or greater and the maximum replacement by weight of the portland cement be 50%.

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## APPENDIX

ANALYSES OF CEMENTS AND SLAGS AND CHARACTERISTICS  
OF FRESH CONCRETE

Table A-1

## Chemical and Physical Analyses of Cements Used

<u>Chemical, (%)<sup>a</sup></u>	<u>C1</u>	<u>C2</u>
SiO <sub>2</sub>	21.7	21.0
Al <sub>2</sub> O <sub>3</sub>	4.1	5.1
Fe <sub>2</sub> O <sub>3</sub>	3.4	2.2
CaO	63.4	64.3 <sup>b</sup>
MgO	3.5	3.0
SO <sub>3</sub>	2.5	2.9
Total Alkalies	0.49	0.68
C <sub>3</sub> S	53.6	55.0 <sup>b</sup>
C <sub>3</sub> A	5.1	9.8
<u>Physical</u>		
Fineness (Blaine)	3,800	3,660

<sup>a</sup>Average of 2 values, one provided by the supplier

<sup>b</sup>Furnished by the supplier

Table A-2

## Chemical and Physical Analyses of Slags Used

<u>Chemical (%)</u>	<u>S1<sup>a</sup></u>	<u>S2</u>
SiO <sub>2</sub>	33.7	34.4
Al <sub>2</sub> O <sub>3</sub>	11.2	8.4
Fe <sub>2</sub> O <sub>3</sub>	0.4	0.7
CaO	38.1	39.3
MgO	13.0	12.1
SO <sub>3</sub>	0.1	0
Total Alkalies	0.42	0.47
 <u>Physical</u>		
Fineness (Blaine)	5,753	4,864
Sp. Gr.	2.92	2.91

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<sup>a</sup> Average of 2 values, one provided by the supplier.

Table A-3

The Requirements for VDH&T A3 (General Use) and  
A4 (Bridge Deck) Concretes

<u>Requirements</u>	<u>A3</u>	<u>A4</u>
Design Min. Lab. Compressive Strength at 28 days	3000 lbf/in <sup>2</sup>	4500 lbf/in <sup>2</sup>
Aggregate Size Number	57	57
Nominal Max. Aggregate Size	1 in	1 in
Min. Cement Content	588 lb/yd <sup>3</sup>	635 lb/yd <sup>3</sup>
Max. Water-Cement Ratio	0.49	0.45
Slump	1-5 in	2-4 in
Air Content	6±2%	6½±1½%

Table A-4

Freshly Mixed Concrete Characteristics  
as an Average of Two Batches

<u>Material Combination</u>	<u>Air, %</u>	<u>Slump, in</u>	<u>Unit Wt. lb/ft<sup>3</sup></u>
C1	6.7	2.6	143.8
C1S1-40	6.8	3.2	142.4
C1S1-50	6.8	3.0	143.2
C1S1-65	6.8	3.0	143.2
C1S2-40	7.4	2.8	143.0
C1S2-50	6.5	3.2	144.0
C1S2-65	7.2	2.9	142.2
C2	7.2	2.5	143.6
C2S1-40	6.6	2.5	143.4
C2S1-50	6.7	2.9	143.6
C2S1-65	7.1	3.2	142.2
C2S2-40	7.2	2.8	142.8
C2S2-50	7.4	3.2	141.8
C2S2-65	6.9	2.7	142.4
C1R	7.8	3.4	142.6
C1S1-50R	7.2	4.6	142.6
C1S2-50R	7.1	4.5	143.0
C2R	6.6	2.5	143.8
C2S1-50R	7.2	3.9	142.2
C2S2-50R	6.4	3.2	143.8