

INTERIM 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 author 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 were used. Slags were used as replacements for portions of portland cement at 40%, 50%, and 65% by weight. This interim 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, air void system of the hardened concrete, and the length change values for 32 weeks. Results of the studies on carbonation and hydration and the additional length change data will be included in the final report.

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, but have equal or better strengths at later ages. The incorporation of slag reduces the permeability of concrete considerably. The resistance to cycles of freezing and thawing of air entrained concretes with and without slags was satisfactory when tested for 300 cycles in 2% NaCl solution. However, generally higher surface scaling was observed on the mixtures with the slags.

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 highway construction.

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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

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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 are 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 are 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 would entail evaluating the pertinent ASTM specification and modifying it as might be required 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 interim

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, air void system of hardened concrete, and length change values for 32 weeks. Results of the studies on carbonation and hydration and the additional length change data will be included in the final report.

Table 1

Combination of Materials and Code Designations

<u>Code Designations</u>	<u>Cement^a</u>	<u>Slag^b</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

^aCement 1 was low alkali Type I-II, cement 2 was high alkali Type I.

^bSlag 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 (Na_2O) 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.³ (1,650 kg/m³). The nominal maximum aggregate size was 1 in. (25 mm). 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 (VDH&T) 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.³ (347 kg/m³) 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 lb./in.² (20.7 MPa).

The mixtures with the water reducer were proportioned to meet the new A4 bridge deck concrete requirements of the Department as also given in Table A-3, and contained 635 lb./yd.³ (375 kg/m³) 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 lb./in.² (31.0 MPa) and a maximum ratio of water to cementitious material of 0.45 was used in all these mixtures.

The ingredients for each material combination 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 concrete mixtures 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, petrographic examination, including air void determinations, and length change. The sample preparation, testing, and the results are given 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 Corp. of Engineers, CRD-C 38-73. A cylinder measuring 6 x 12 in. (150 x 300 mm) 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. (100 x 200 mm) 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) ^a	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

^a Numbers in parentheses are the values in °F.

To convert to °C use --

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$$

Table 4

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

Material Combination	Compressive Strength				Flex. Str.
	7 days	14 days	28 days	56 days	28 days
C1	100 (3,680) ^a	100 (4,400)	100 (4,850)	100 (5,315)	100 (684)
C1S1-40	83	95	106 ^b	110	101
C1S1-50	84	100	100 ^b	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 ^d (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 ^d	104	112	105
C2S2-50R		92	102	105	103

^aNumbers in parentheses are the values in lb./in.². To convert into kPa, multiply by 6.89.

^bAverage of 2 specimens.

^cNo specimens because of limited batch size.

^dAverage 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 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. (75 x 75 x 285 mm) 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. (50 mm) thick and 4 in. (100 mm) in diameter and were cut from the top of standard 4 x 8 in. (100 x 200 mm) 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>Charged 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 given in the FHWA report as an indication of high permeability. 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.

Curing types CC and LC were included in the study to simulate field curing conditions and to observe the effect of lime on the carbonation of the surface layer. This phenomenon will be studied in petrographic examinations of ultra-thin sections and the results will be included in the final report.

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 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 separate 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.

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. From each batch of concrete a beam measuring 3 x 4 x 16 in. (75 x 100 x 400 mm) was prepared for the petrographic examination. A slab from each of the beams was cut and lapped and subjected to linear traverse analysis. The rest of the slab will be used in the study of the nature of carbonation and hydration of the concretes. Some portions of some of the slabs were cured with the curing compound, or lime water and the curing compound, similar to that used for some of the specimens in the freezing and thawing tests. The final report will include a detailed explanation of the sample preparation for the petrographic examination.

The results, summarized in Table 7, indicate that for all the concretes the total void contents determined on hardened concrete were closer 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 (0.04 in.) in diameter, were generally 2% or less as 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.⁻¹ (24 mm⁻¹) and the spacing factor less than 0.008 in. (0.20 mm), values that are considered necessary for the protection of saturated concretes from cycles of freezing and thawing. (8) These results are consistent with the results of the freeze-thaw tests that showed satisfactory performance. However, the higher scaling observed on some specimens with slag cannot be attributed to inadequacies in the void system, and can thus be considered a surface phenomenon which is being investigated.

Table 7

Air Void System of Hardened Concrete

Material Combination	Void Content, %			Specific Surface, in. ⁻¹	Spacing Factor, in.
	>1 mm	<1 mm	Total		
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

Note: 1 in. = 25.4 mm

Length Change

The length change of some of the concretes, shown in Table 8, stored in the moist room or kept in the laboratory air were determined in accordance with ASTM C157. Two specimens measuring 3 x 3 x 11½ in. (75 x 75 x 285 mm) with gage studs at both ends were prepared from each batch of concrete. At the time of removal from the molds, the lengths of the specimens were measured, then the specimens were cured in the moist room until they reached an age of 28 days. Then 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 32 weeks and the results are summarized in Table 8

Table 8

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

Material Combination	Moist Cured			Air Dried		
	4 wk.	16 wk.	32 wk.	4 wk.	16 wk.	32 wk.
C1	0.003	0.009	0.008	-0.036	-0.048	-0.060
C1S1-40	.006	.016	.016	- .036	- .052	- .062
C1S1-50 ^a	.007	.014	.012	- .037	- .052	- .061
C1S1-65	.013	.018	.012	- .035	- .057	- .072
C1S2-50	.011	.020	.015	- .035	- .054	- .068
C2 ^a	.007	.011	.011	- .045	- .082	- .086
C2S1-50	.006	.009	.008	- .026	- .054	- .065
C2S2-50	.013	.017	- .002	- .053	- .076	- .090
C1R	.009	.007	.006	- .055	- .072	- .067
C1S1-50R	.019	.025	.024	- .034	- .046	- .053
C1S2-50R	0.026	0.036	0.030	-0.045	-0.056	-0.062

^aOne beam for the moist cured condition.

for 4, 16, and 32 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.

Although some of the individual measurements showed erratic behavior, 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.(9) The drying shrinkage values for specimens stored in the air were, in general, mixed. In a recent study utilizing slag with a high activity index, the concrete length change tests on controls and mixtures with slag had shown relatively normal volume change characteristics; however, mixtures with slag were found to have slightly increased shrinkage as compared to the controls.(10) The drying shrinkage had been related to the SO₃ content of the mixture on tests with mortar prisms, with the higher SO₃ contents exhibiting lower shrinkage.(10) The length change test will be terminated at an age of 1 year and the results will be included in the final report.

CONCLUSIONS

Based on the results of the laboratory investigation 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 only portland cement. 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 slags.
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 better compressive strengths were obtained for concretes with slags, 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 percentage of control strength 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. At later ages, the strengths were about equal to or better 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 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 better than those of the controls, except that the slag with a lower activity index had lower strengths at the 65% replacement by as much as 9%.
7. Mixtures containing slags 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. 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 the slags.
9. The linear traverse data for all the mixtures indicated the presence of a satisfactory air void system.
10. The length change data available for 32 weeks were variable and the tests are continuing.
11. Based on the results obtained to date, 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 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 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, freeze-thaw durability, and volume change, 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, (%)^a</u>	<u>C1</u>	<u>C2</u>
SiO ₂	21.7	21.0
Al ₂ O ₃	4.1	5.1
Fe ₂ O ₃	3.4	2.2
CaO	63.4	64.3 ^b
MgO	3.5	3.0
SO ₃	2.5	2.9
Total Alkalies	0.49	0.68
C ₃ S	53.6	55.0 ^b
C ₃ A	5.1	9.8
<u>Physical</u>		
Fineness (Blaine)	3,800	3,660

^aAverage of 2 values, one provided by the supplier

^bFurnished by the supplier

Table A-2

Chemical and Physical Analyses of Slags Used

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

^aAverage 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 lb./in. ²	4500 lb./in. ²
Aggregate Size Number	57	57
Nominal Max. Aggregate Size	1 in.	1 in.
Min. Cement Content	588 lb./yd. ³	635 lb./yd. ³
Max. Water-Cement Ratio	0.49	0.45
Slump	1-5 in.	2-4 in.
Air Content	6±2%	6½±1½%

Note: 1 in. = 25.4 mm;

1 lb./in.² = 6.89 kPa;

1 lb./ft.³ = 16.0 kg./m³

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.³</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

Note: 1 in. = 25.4 mm;

1 lb./ft.³ = 16.0 kg/m³