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FINAL REPORT

INVESTIGATION OF CONCRETE CONTAINING SLAG -- HAMPTON RIVER BRIDGE

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.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia
Department of Highways and Transportation and
the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

May 1986
VHTRC 86-R39

-2536

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ABSTRACT

The study evaluated the properties of concretes containing slag in a 50% replacement of the portland cement to assess their suitability as an alternative to the portland cement concretes normally used in the construction of bridge substructures. For the major portion of the study, samples were obtained from freshly mixed concrete used in the construction of the substructure for the Rte. 143 bridge over the Hampton River and also from a failed pier footing for the bridge. In the laboratory, a limited investigation was made of the effects of temperature on concretes with and without slag. The results indicate that concretes containing quality slag will perform satisfactorily in bridge substructures. However, it has been shown that strength development in concretes containing slag is more adversely influenced by cold weather than is that of concretes without slag. Also, it is noted that in cold weather there may be a significant delay in the time of set.

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INTRODUCTION

Granulated iron blast furnace slag is formed by rapidly chilling the molten slag. It consists essentially of silicates and aluminosilicates of calcium and other bases. When finely ground, and meeting applicable ASTM specifications, this material is suitable for use as a replacement for a portion of the portland cement in concrete. The substitution rates are usually about 50% or less, but can be higher in some applications. The slag can be blended with portland cement at the cement plant or added during mixing of the concrete. The latter procedure provides greater flexibility in proportioning.

Research has indicated that properly used, good quality slags improve the workability of concrete, reduce its permeability, segregation, bleeding, and heat of hydration, and increase its resistance to deterioration from sulfate solutions and alkali-aggregate reactions. Also, the ultimate strengths of slag concretes are higher than those of similar concretes using only portland cement as the cementitious material.(1,2,3) However, there are also possible disadvantages in some applications, since strength development at early ages is slower for concretes containing slag, especially in cold weather and at increased replacement rates, and the time of set is longer than that for similar mixtures without slag.

Because of its influence on the service life of highway facilities, the durability of concrete is an important consideration, and laboratory investigations at the Research Council, as well as research elsewhere, have shown that the incorporation of slag significantly reduces the permeability of concrete and thus enhances its durability. In light of the potential advantages to be gained through the use of slag in concrete, plans were drawn for using slag concrete mixtures in the construction of a bridge substructure and evaluating their performance.

OBJECTIVE

The objective of the study was to assess the suitability of concretes containing slag as an alternative to the portland cement concretes normally used in the construction of bridge substructures.

SCOPE

Selected for the evaluation was a bridge to be constructed to carry Rte. 143 over the Hampton River in the city of Hampton. For the substructure, the contractor was given the option of using concrete containing slag as replacement for 50% of the portland cement. It was anticipated that the concrete containing slag would be placed over an approximately two-year period, and visits to the job site were planned at different times of the year to evaluate the effects of variations in temperature on the curing of the concrete. The first trip was made at the end of August 1983 during hot weather. At that time, samples from two batches of the concrete being placed were prepared for tests in both the fresh and hardened states. It was planned that a visit would also be made during cold weather, but in December 1983 a failure of a pier footing made with slag concrete resulted in the contractor cancelling his plan for further use of this concrete in cold weather. Consequently, the planned sampling and testing of freshly mixed field slag concretes placed during cold weather could not be accommodated. Samples from the failed pier footing were taken for tests.

Since no alternative field project was available in which essentially the same materials would be used in cold weather, a laboratory investigation was undertaken to determine the effects of the curing temperature on the compressive strength of concretes with and without slag. For this study, 108 test cylinders were prepared from four batches of concrete.

MATERIALS AND MIXTURE PROPORTIONS

Field

For the bridge substructure, a type II cement and a slag meeting the requirements of ASTM C 989 Grade 120 were used. The fine aggregate was a siliceous sand with a fineness modulus of 2.80 and a specific gravity of 2.62. The coarse aggregate was gravel with a specific gravity of 2.64 and a unit weight of 104 lb/ft^3. The specific gravity of the slag was 2.95. Neutralized vinsol resin was used as the air-entraining agent.

The mixtures were prepared to meet the requirements of the Virginia Department of Highways and Transportation for class A3 general use concretes shown in Table 1, except that slag was used to replace 50% of the portland cement.

TABLE 1

Requirements for Class A3 General Use Concretes

Design min. lab. comp. strength at 28 days	3,000 psi
Aggregate size number	57
Nominal maximum aggregate size	1 in
Minimum cement content	588 lb/yd^3
Maximum water/cement ratio	0.49
Slump	1 to 5 in
Air content	6% ± 2%

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Laboratory

For the laboratory investigation, control mixtures and experimental mixtures containing a type II cement and slag from the same sources as those used in the field were batched. The chemical and physical analyses of the cement and slag are shown in Table 2. The fine aggregate was a siliceous sand and the coarse aggregate was crushed granite gneiss. The mixture proportions are given in Table 3. A commercially available neutralized vinsol resin was used as the air-entraining agent.

TABLE 2

Chemical and Physical Analyses of Cement and Slag

Chemical, %	Cement	Slag
SiO_2	21.0	33.7
Al_2O_3	4.8	11.2
Fe_2O_3	4.1	0.4
CaO	63.3	38.1
MgO	2.4	13.0
SO_3	2.5	0.1
Total Alkalies	0.79	0.42
Physical		
Fineness, cm^2/g	3,556	5,753

TABLE 3

Mixture Proportions, lb/yd^3

Material	Control Concrete	Slag Concrete
Cement	588	294
Slag	0	294
Water	282	282
Coarse agg.	1,839	1,839
Fine agg.	1,175	1,156

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FIELD TESTING

In the field, samples of the concrete containing slag were prepared for tests at both the freshly mixed and hardened stages. In addition, samples were taken from a failed footing.

Freshly Mixed Concretes

The concrete containing slag was furnished in ready-mix trucks. During late August, two of the trucks were randomly selected and sampled. The characteristics of the freshly mixed concrete and the air temperatures at the time of sampling are given in Table 4. The freshly mixed concretes were tested for slump following ASTM C 143 and for air content following ASTM C 231. The water/cement ratio (w/c) was 0.44.

Hardened Concretes

From each batch, twelve 4-by 8-in cylinders were prepared for the compressive strength tests, rapid permeability tests, and air-void analysis; three 3-by 4-by 16-in beams were made for the rapid freeze-thaw tests, and four 3-by 3-by 11 1/4-in beams for flexural strength and drying shrinkage tests. The test results are summarized in Table 5 and discussed below.

Compressive and Flexural Strengths

The compressive strengths at 14, 28, and 56 days were determined following AASHTO T 23, except that neoprene pads in steel end caps were used for capping. The strength values were considerably higher than the required minimum values. The flexural strengths were determined at 28 days following ASTM C 78, and were found satisfactory.

Permeability

The rapid permeability tests were conducted in accordance with AASHTO T 277. The specimens were moist cured for 2 weeks and then air dried for 6 weeks. In the test, a voltage is applied across a specimen cut from the top 2 in of the cylinder and the current passing through the specimen in 6 hours is determined in coulombs. The values obtained for the test concretes indicate a satisfactory resistance to chloride intrusion.

Drying Shrinkage

The drying shrinkage was determined following ASTM C 157. The specimens were moist cured for a month and then kept in the laboratory ambient air until tested. The shrinkage values at 64 weeks, given in Table 5, were satisfactory.

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TABLE 4

Characteristics of Freshly Mixed Concrete

Batch	Slump, in	Air, %	Temperature, °F	
			Concrete	Air
1	1.9	4.2	89	95
2	5.0	6.5	88	92

TABLE 5

Properties of Hardened Concrete

Property	Batch 1	Batch 2
Comp. str.[a], psi		
14-day	4,590	4,110
28-day	5,940	5,540
56-day	6,020	6,050
Flexural str.[b], psi		
28-day	700	685
Permeability[b],		
Coulombs	1,870	3,000
Drying shrinkage[b], %		
64 weeks	0.049	0.052
Freeze-thaw data[a] at 300 cycles		
Weight loss, %	3.2	4.1
Durability factor	102	107
Surface rating	1.5	1.6
Linear traverse		
Air voids, %		
<1 mm	2.3	3.4
>1 mm	1.0	0.8
Total	3.3	4.2
Specific surface, in^{-1}	594	719
Spacing factor, in	0.0099	0.0072

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[a] Average of 3 specimens
[b] Average of 2 specimens

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Resistance to Freezing and Thawing

The resistance of the concretes to cycles of freezing and thawing was determined using ASTM C 666 Procedure A with two modifications to better simulate field conditions. One modification was that the specimens were air dried for 1 week in addition to the 2 weeks of moist curing noted in the ASTM method. The other modification was that 2% NaCl was added to the test water. The established acceptance criteria is that at 300 cycles the average weight loss must be 7% or less, the durability factor must be 60 or more, and the surface rating must be 3 or less. The surface rating was determined by estimating the proportion of surfaces having ratings as given in ASTM C 672. The top surface was rated separately from the molded surface, and the final rating for each beam was calculated by averaging the weighted ratings computed for the top and the molded surfaces. The results at 300 cycles indicate that the concretes met the acceptance criteria and thus should provide satisfactory performance.

Air Void System

One sample from each batch was subjected to the linear traverse method described in ASTM C 457 to determine the small, large, and total air void contents, the specific surface, and the spacing factor. The results, summarized in Table 5, indicate that in the first batch the total void content was less than the 4% minimum specified. Also, for that batch the specific surface value was less than 600 in^{-1} and the spacing factor was larger than 0.008 in, the limiting values that are considered necessary for the protection of critically saturated concretes from damage by cycles of freezing and thawing.(4) However, this concrete met the criteria for satisfactory freeze-thaw performance established for the laboratory tests. Concrete from the second batch had satisfactory air void parameters and also met the criteria for freeze-thaw resistance.

Placement Problem

During cold weather concreting, there was a settlement of the forms during placement that resulted in large cracks at the lower end of a pier footing. Consequently, the footing had to be replaced. The failure was attributed to slippage of the friction collars holding the horizontal form work. It was noticed that the initially placed layers of mixture did not develop the stiffness usually developed by concrete without slag. As a result of the failure, the placement of slag concrete on this project during cold weather was discontinued.

The cause of the slippage was not precisely identified. Regardless of the cause of the slippage in this instance, it should be recognized that in cold weather, concretes containing slag can undergo a significant delay in set, and that this could result in higher than normal pressures on vertical forms.(5) Consequently, consideration must be given to this probability in designing the form work for concrete containing slag.

At temperatures of 73°F the time of initial set is typically extended between a half hour and an hour.(1) At temperatures around 40°F, more significant retardation has been observed.(6)

Tests on Concrete from Failed Footing

Four pieces of concrete were obtained from the damaged footing before removal: two from the lower, damaged area and the two from the undamaged, top-middle section.

Strength and Permeability

Tests on the concrete from the pier footing were conducted at an age of about 4 months. A core was obtained from each of the two pieces from the undamaged middle section only. The concrete pieces from the damaged section were not suitable for coring. One core was cut into two pieces and used for compressive strength and permeability tests. The strength was found to be 4,910 psi and the charge passed 5,020 coulombs. The other core, being short, was used in the rapid permeability test only and a value of 2,920 coulombs was obtained. Thus, while this latter value was similar to those obtained in the field tests on slag concrete cited earlier, the result for the first core was higher than expected.

Petrographic Examination

Lapped slab specimens were prepared from each of the four pieces. The petrographic examination indicated that the concretes from the undamaged section of the failed footing had a good paste structure, with a good paste-to-aggregate bond and minimal microcracking. It was noted that the concrete in the second core discussed above contained a bluish green splotch. However, the concrete in the splotched area appeared to be of good quality and difficult to differentiate from that in other areas except for the color. Such splotches are not unusual and have been observed in other concretes containing slag. The samples from the damaged area had voids caused by the influx of water through the wide cracks, as would be expected. However, water had not generally mixed with the concrete in the interior of the samples, which appeared to be of good quality.

LABORATORY TESTS

Four 2 ft^3 batches of concrete were prepared to investigate the effects of curing temperature on the strength development of concrete mixtures with and without slag. Each batch was duplicated for assurance. From each batch, 27 cylinders were made for tests at 7, 14, and 28 days and at curing temperatures of 40°, 73,° and 100°F. The specimens were prepared at room temperature, and 9 of them were cured in the laboratory air in the

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molds for 1 day and then in the moist room until the time of test. Each value is a result of tests on 3 cylinders. A second set of 9 specimens were kept in the molds in a temperature-controlled chamber at 40°F for 7 days. This procedure was to assure that the specimens attained enough strength to resist damage when being removed from the plastic molds. After the 7-day period, the second set were taken from the molds and placed in lime saturated water at 40°F until the time of test. The third set of 9 specimens were placed in a water tank at 100°F in the molds for 1 day. The molds then were stripped and the specimens were immersed in the lime saturated water at 100°F. When the specimens were kept in molds, precautions were taken to prevent loss of moisture from the concrete.

The slumps, air contents, and unit weights for the freshly mixed concretes are summarized in Table 6. The slumps ranged from 2.8 to 4.2 in and the air contents from 5.2% to 7.0%. All these values were within the acceptable limits for class A3 general use concretes.

The compressive strength data are given in Table 7.

TABLE 6

Fresh Concrete Characteristics

Batch	% Slag	Slump, in	Air, %	Unit Weight, lb/ft^3
1	0	4.2	6.9	144.8
2	0	2.8	5.2	146.0
3	50	3.1	7.0	143.6
4	50	2.9	5.2	145.2

TABLE 7

Compressive Strength Data
(Values are averages for 6 specimens, 3 from each batch)

		Strength, psi		
Mixture	Curing Temp, °F.	7 Day	14 Day	28 Day
Control	40	3,110	3,700	4,580
	73	3,580	4,210	4,820
	100	3,700	3,720	3,820
Slag	40	1,590	2,500	3,620
	73	2,710	3,840	4,700
	100	3,460	3,860	4,260

These results indicate that when cured at 73°F concretes with slag had 28-day strengths approximating those of the controls. At earlier ages the controls had higher strengths at 73°F. When cured at 40°F, the concretes with slag had lower strengths than the controls. The differences were considerably larger at earlier ages. When cured at 100°F, the concretes with slag had lower strengths than the controls at 7 days, but were higher at 14 days and 28 days.

At ambient temperatures between 73°F and 40°F setting times of slag concrete become longer and the strength development significantly slower as the temperature decreases. Thus, special precautions or revised construction processes may be necessary in cold weather when using slag concretes. Field evaluations would be necessary to determine the lowest practicable temperatures and the applicable construction processes for the placement of such concretes.

CONCLUSIONS

Based on the results of the limited tests in the field and the laboratory, the following conclusions are drawn.

1. Normally cured concretes containing slag as a 50% replacement of the portland cement exhibited satisfactory 28-day compressive strengths, permeabilities, freeze-thaw resistance, and drying shrinkage values. However, at early ages the strengths of the slag concretes were lower than those of the controls.

2. When cured at low temperatures (40°F) the mixtures with slag exhibited lower strengths at ages up to and including 28-days compared to the controls. When cured at high temperatures (100°F) the concretes with slags exhibited higher strengths than the controls, except for the tests made at 7 days.

3. In cold weather, concretes containing slag could undergo a significant delay in time of set. This probability should be taken into account when establishing placement procedures, and special precautions should be taken to avoid potential problems.

4. Splotchy areas which show variations in color distribution have been observed in concretes with slag, but they do not appear to be indicative of quality.

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RECOMMENDATION

Slags meeting the requirements of ASTM C 989 and with a sufficient activity index may be used to replace 50% of the portland cement in concretes used as alternates to class A3 concretes containing no slag. It is recommended that during mild or hot weather (ambient temperatures at or above 73°F) the use of such concrete be permitted. However, since in cold weather concretes containing slag are likely to have longer times of set and lower strengths at early ages, special precautions such as reduced percentages of slag and the use of thermal blankets during curing may be needed to avoid potential problems. This study did not attempt to investigate the optimum amount of slag for use in concrete to be placed during cold weather or the lowest temperature at which it is practicable to place such concretes.

ACKNOWLEDGEMENTS

Special thanks are expressed to the field personnel who assisted in the accumulation of data at the bridge site.

Appreciation is expressed to Mike Burton and Leroy Wilson for the preparation and testing of the specimens, and to Ms. Hollis Walker and Bobby Marshall for the petrographic examination.

Special thanks are extended to Arlene Fewell for typing the report and to Harry Craft for reviewing it.

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