

Use of Concrete Containing Slag Cement in Transportation Structures in Virginia

by C. Ozyildirim

Synopsis: Slag cement was introduced to Virginia Department of Transportation (VDOT) in the early 1980s. Laboratory investigations showed that slag cements can be used as an alternative to conventional portland cement concretes in replacement rates up to 50% for pavements and bridge structures. Concrete containing slag cement had lower permeability than the conventional portland cement concrete.

Since the mid 1980s, slag cement has been successfully used by VDOT in bridge structures and pavements to reduce permeability and improve the durability of concrete. In large footings, slag cement has been used at a replacement rate of 75% to control the temperature rise and to reduce permeability. Currently, slag cement is used in high-performance concretes to obtain high compressive strength and low permeability.

Slag cement is also used in ternary blends with portland cement and fly ash or silica fume to lower permeability, improve durability, and obtain the desired early strengths.

Keywords: bridge; durability; mass concrete; pavement; permeability; slag; slag cement; strength; temperature control.

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INTRODUCTION

Iron blast furnace slag is a nonmetallic product consisting essentially of silicates and aluminosilicates of calcium. This slag develops in a molten condition simultaneously with iron in a blast furnace.¹ Molten slag from the furnace is rapidly quenched with water forming a glassy, granulated material that is dried and ground to a fine powder.² Powdered slag possesses cementing properties either alone or with calcium hydroxide produced during the hydration reaction of portland cement. Use of slag cement makes the binder denser and leads to reduced permeability, increased strength and durability, and reduced temperature rise in mass concrete.³

When slag replaces 25% or more of the portland cement, then there can be a delay in setting time, especially in cold weather.¹ Setting time can also be affected by the amount of slag and portland cement, the water-cementitious materials ratio (w/cm), and the characteristics of the portland cement. Although concrete strength development is slower for the first few days, concrete containing slag cement can obtain higher ultimate strengths.²

The Virginia Department of Transportation (VDOT) started experimenting with slag cement in the early 1980s with the construction of the slag granulation facility in Sparrows Point, Maryland. Based on the initial laboratory work, VDOT permitted the use of slag cement as an alternative to conventional portland cement concrete (PCC). Since that time, concrete with slag cement has been used successfully in bridge structures, pavements, and mass concrete applications.

PURPOSE AND SCOPE

This paper summarizes the laboratory work with and subsequent field applications of slag cement conducted by VDOT. Concrete with slag cement was initiated as an alternative to conventional PCC mixtures. The workability, ultimate strength, and durability were evaluated. Binary cementitious system of portland cement with slag, and ternary systems of portland cement with slag and silica fume or slag and fly ash were also included in the study; they are used for reduced permeability without reduction in early strengths, especially in cold weather. Strength, permeability, heat rise, and resistance to freezing and thawing and alkali-silica reactivity (ASR) were determined in the laboratory. Field applications in bridge structures, pavements, and mass concrete (footings) illustrate the benefits of slag cement in concrete.

LABORATORY WORK

Before the inclusion of slag cement in transportation structures in Virginia, concretes with and without slag cement were tested and compared. The fresh and hardened properties of these concretes were determined to ensure that workable, strong, and durable concretes could be achieved. Concerning durability, in the early 1980s, concretes were mainly tested for resistance to freezing and thawing. Then, permeability and resistance to ASR drew attention. To determine permeability, the rapid chloride permeability and ponding tests were used. Laboratory work indicated that slag cement did resist ASR and did lower permeability, which is essential for durability, and in large amounts would be highly beneficial in controlling heat rise in mass structures.

In achieving satisfactory strength, there were concerns that at large replacement rates, early strengths would be low. In response to such concerns, ternary systems where lower amounts of slag cement are used were evaluated. The laboratory studies leading to the widespread use of slag cement in VDOT structures are summarized in the following sections.

Early testing

The goal of the work in the early 1980s was to evaluate the effect of slag cement on the properties of concrete used in transportation facilities. These studies made comparisons with PCC with respect to time of set, heat of hydration, compressive strength, flexural strength, permeability, resistance to freezing and thawing, length change, and petrographic examinations for air voids, carbonation, and hydration.⁴

Cements and slag cements from two sources and 20 material combinations were tested.⁴ One of the cements was Type I-II with an alkali content of 0.49% and the other one was Type I cement having a 0.68% alkali content. The two slag cements had different slag activity indexes; Grade 120 and Grade 100. All of the batches contained a commercially available vinsol resin air-entraining admixture. Some of the batches had a water reducing and

retarding admixture, and were proportioned to meet bridge deck requirements. These batches had a total cementitious material of 635 lb/yd³ (377 kg/m³), a minimum 28-day compressive strength of 4500 psi (31 MPa) [currently the minimum strength requirement is 4000 psi (28 MPa)], and a maximum water-cementitious material ratio (*w/cm*) of 0.45. Additional mixtures without the retarding admixture met the requirements for substructure concrete and had a cementitious materials content of 588 lb/yd³ (349 kg/m³), a minimum 28-day strength of 3000 psi (21 MPa), and a *w/cm* of 0.48. The maximum specified *w/cm* for substructure concrete is 0.49. Slag cement replacement rates were 50% in the mixtures with higher cementitious material and the retarding admixture for the bridge structure concrete, and 40, 50, and 65% in the mixtures without retarding admixture for the substructure concrete.

The results indicated that the addition of slag provided some improvements in workability.⁴ Also the time of initial setting was delayed by about an hour and the final setting by two hours. The temperature rise at early ages was lower for the concrete containing slag, and the maximum temperature was also lower. The mixtures with the higher cementitious material had higher temperature rise as expected. After the maximum temperature, the temperature of the control concrete dropped at a faster rate than that of the mixture with the slag concrete.

All of the mixtures had satisfactory compressive strengths exceeding 3000 psi (21 MPa) at 7 days and beyond. Seven-day strengths were lower for the concretes containing slag, but their ultimate strengths were higher than the control batches except at the 65% replacement rate. The concretes with higher-grade slag displayed higher strengths. Mixtures with high-alkali cement had higher early strengths. With the exception of the mixture that replaced 65% of the portland cement, the flexural strengths of the slag concretes containing slag at 28 days were about equal to or higher than those of the control.⁴

Permeability was determined using the test method described in an FHWA report, which was later adopted as the rapid chloride permeability (penetrability) test, AASHTO T 277 and ASTM C1202.⁵ The results for all of the test mixtures indicated high or moderate permeability. This elevated permeability was due to limited, insufficient curing time, where the specimens were moist cured for 2 weeks and then air-dried for 6 weeks. Regardless, concretes with slag cement had lower permeability, where the reduction in permeability was proportional to the amount of portland cement replaced by slag. Furthermore, petrographic examinations revealed less calcium hydroxide in the slag concretes, and the fluorescent dyed epoxy was unable to penetrate slag concrete, which is indicative of low permeability.⁴

The resistance to freezing and thawing in the presence of 2% NaCl was satisfactory, even though, higher surface scaling was observed in concretes with slag cement. The acceptance criteria for the weight loss was 7% or less, and for surface rating, 3 or less according to ASTM C672. The durability factors were above 95 for all mixtures. Drying shrinkage values were also similar.

Laboratory testing also evaluated the temperature effects on compressive strength.⁶ Although the results indicated that all of the various concrete mixtures cured at lower temperatures had lower strengths at early ages, concrete with slag cement was more sensitive to temperature than the control concrete. However, concretes cured at lower temperature had higher ultimate strength.

Low-permeability concrete

The introduction of the rapid chloride permeability test made low permeability evaluations convenient. As discussed above, these tests showed the benefits of concrete with slag cement; however, the curing method used in the early studies did not indicate the full potential of the pozzolans or slag cements. Further laboratory work indicated the importance of time on the permeability of concrete, where permeability decreased with time, as shown in Fig. 1.⁷ Concretes with slag cement had low permeability. Also, concretes with lower *w/cm* had lower permeability, especially for concretes with slag cement as shown in Fig. 2.

Long-term permeability can be estimated at 28 days by accelerating the curing process at higher temperatures. To show the effect of curing temperature, laboratory testing studied various temperatures during curing.⁶ The specimens were cured at 50°F (10°C) for 28 days, 73°F (23°C) for 28 days, one week at 73°F (23°C) followed by three weeks at 100°F (38°C), one week at 73°F (23°C) followed by three weeks at 122°F (50°C), and one week at 73°F (23°C) and then outdoors for a year. The curing performed at 73°F (23°C) was done in a moist room and specimens cured at 50 or 100°F (10 or 38°C) were in lime-saturated water. The results, shown in Fig. 3, indicated that concretes had a lower 28-day permeability when cured at higher temperatures. Concrete containing slag subjected to accelerated curing and tested at 28 days or kept outdoors after 7 days of moist curing and tested at one year had similar permeability as the one-year specimens cured at 73°F (23°C). Currently, VDOT cures permeability specimens for 1 week at room temperature and then 3 weeks at 100°F (38°C), and tests the specimens at 28 days.⁸

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Another less contested test procedure for permeability is the ponding test, where the intrusion of chlorides serves as an indication of a concrete's permeability.⁷ Both slag concretes and control concretes having a w/cm of 0.45 were ponded for extended period of time and compared with each other. After 30 months of ponding, chlorides were detected down to the 2 in. (50 mm) depth in the control specimens but there were no chlorides below a 1 in. (25 mm) depth in the slag concretes.⁷

Ternary system

Since initial studies showed that low temperatures slow down strength development and reduction in permeability, especially when slag cement replaces a large portion of the portland cement, scientists extended their research to a ternary system that combined portland cement, slag cement, and silica fume.^{9,10} With proper curing and the proper amount of slag cement low permeability is expected. In the ternary system with silica fume low and very low permeability were achieved using low amounts of slag cement as shown in Fig. 4.¹⁰ Similar to previous tests, high temperature benefited ternary blends in reducing permeability. Again, accelerated curing can help to determine long-term permeability at 28 days.

The one- and seven-day strengths were higher in the control concretes, as shown in Fig. 5. Ternary blends had 7-day strengths close to the control and higher than binary systems. Ultimate strengths were higher in the concrete containing slag than the controls.

Ternary system of slag and fly ash was successfully used in a bridge deck on Route 11 over the New River and Norfolk Southern Railroad tracks. The mix proportions are given in Table 6. The test results from 31 sublots summarized in Table 6 indicate satisfactory strength and very low permeability and small variability.

Alkali-silica reactivity

Laboratory work also addressed ASR and showed that if cements with low alkali content are not available, slag cement can help inhibit ASR.¹¹ Tests conducted in accordance with ASTM C441 showed the benefit of slag cement in reducing expansion due to ASR. For satisfactory resistance to ASR, expansion should be 0.1% or less at 56 days when tested with ASTM C441.¹² A table in the VDOT Manual of Instructions shows that ASR protection is not needed for cement alkali contents of 0.45% or less. However, for higher alkali contents up to 1%, Class F fly ash, silica fume, or slag cement can be used at different percentages based on the alkali content of the cement. If the alkali content is between 0.45% and 0.60%, a minimum 25% slag cement (Grade 100 and above), for alkali content 0.60% to 0.90% a minimum of 35%, and between 0.90% and 1%, a minimum of 50% slag cement is required. Ternary systems with slag and silica fume also indicated improved resistance to ASR.¹¹ If the cementitious system is different than that in the VDOT table, a test conforming to ASTM C441 is specified and expansion of 0.1% or less at 56 days is required.

FIELD APPLICATIONS

Bridge structures

First application—The promising test results of the early laboratory work prompted the use of slag cement in the substructure of the bridge on Route 143 over the Hampton River in the city of Hampton, Virginia.¹³ The minimum cementitious material content was 588 lb/yd³ (349 kg/m³) and the minimum 28-day design strength 3000 psi (21 MPa). The slag cement was used at the 50% replacement rate and the w/cm was 0.48. The strength and permeability values of concrete sampled in August 1983 are given in Table 1. The permeability specimens were moist cured for 2 weeks and then air-dried for 6 weeks, which is an insufficient curing period. The slag concrete obtained high strength and low to moderate permeability.

During placement in cold weather in December 1983, formwork settlement resulted in a large crack at the lower end of a pier footing. The failure was attributed to slippage of friction collars holding the horizontal formwork. It was noticed that the initially placed layers of mixture did not set as the subsequent layers were placed over. Concrete pieces were obtained from the failed footing before removal. A core at 4 months had a satisfactory compressive strength of 4910 psi (33.9 MPa). The permeability of two cores was 5020 and 2920 coulombs. The movement and the cracking could have affected the permeability values. This experience indicated that in cold weather, care should be exercised in preparing sturdy formwork and delayed setting and strength development should be accounted for.

HPC structures—Low permeability is essential for longevity in bridge structures and is the focus of high-performance concrete (HPC) in Virginia.^{8,14} In the 1990s, the Federal Highway Administration initiated the HPC program. VDOT

had used HPC in some structures because of the addition of Class F fly ash or slag cement. For example, the first slag cement application on Route 143 is explained above. Also, all concrete placed in bridges since 1992 can be considered HPC since those concretes contain a pozzolan or slag cement for inhibiting ASR. However, since the mid 1990s, VDOT has been testing those designated HPC for strength and permeability. Some projects have required that prestressed beams have strengths exceeding 7000 psi (48 MPa) and a maximum permeability of 1500 coulombs. The maximum permeability has been specified at 2500 coulombs for bridge decks and 3500 coulombs for substructure. Specimens are moist cured 1 week at 73°F (23°C) and for an additional 3 weeks at 100°F (38°C).

VDOT has used HPC for constructing seven bridges from 1995 to 1997. The bridge on Route 40 over Falling River is an example of how the slag cement provided low permeability concrete in the substructure and the deck.¹⁵ The bridge deck had strengths that were double the minimum specified strength and permeability that was much less than that required as shown in Table 2. This project had the added difficulty of being placed in cold weather. To protect the concrete containing 50% slag cement from the cold temperatures, the contractor placed heaters on the pier caps and heated the deck from the underside.

Slag cement has been successfully used in Virginia projects with normal weight HPC with strengths exceeding 7000 psi (48 MPa). The first HPC lightweight concrete structure in Virginia is the bridge built in 2001 that carries Route 106 over the Chickahominy River. This bridge had beams made with lightweight concrete containing slag cement with a minimum 28-day compressive strength of 8000 psi (55 MPa).^{16,17} Table 3 summarizes the mixture proportions, strength, and permeability of the concrete used in the beams.

Construction and experience with HPC structures indicated that concretes with slag cement had satisfactory workability and strength. The lab results and initial performance also indicate satisfactory durability.

Self-consolidating concrete

The introduction of self-consolidating concrete (SCC) has opened new horizons for concrete. SCC has high flowability, eliminating the problem with consolidation, and therefore enhances the strength and durability of concrete. In addition, SCC enables concrete placement in heavily reinforced and congested areas. Other advantages include rapid placement of concrete and smooth surfaces of formed elements. VDOT constructed its first SCC arch bridge in Fredericksburg in 2001.¹⁸ The SCC for this project contained slag cement and had high workability, low permeability, and satisfactory strength as shown in Table 4.¹⁸ In 2003, two bulb-T beams with a 45 in. (1.1 m) depth and 60 ft (18 m) length were cast using SCC. The mixture proportions and data on strength and permeability are given in Table 5. This project indicated that concrete with slag cement can be successfully used in applications where high flow is needed and the resulting concrete has satisfactory strength and durability based on lab testing and initial field exposure.

Pavements

The benefit of slag cement in pavements was well demonstrated in an experimental project using jointed plain concrete pavement on I-64 in Newport News.¹⁹ In this project, large-sized aggregate and combined grading were tried. Most of the project used 1 in. (25 mm) nominal maximum size aggregate (NMS) and Class F fly ash. However, in two experimental sections, the producer used concrete with slag cement. One section with concrete containing slag cement used 1 in. (25 mm) NMS, and another 2 in. (50 mm) NMS for comparison. The mixture proportions and the permeability and strength of these concretes are shown in Table 7. The results show that both sections with concrete containing slag with different aggregate size had satisfactory strengths and low permeability. The use of large-size aggregate resulted in a reduction in the water and cement contents; however, these reductions were minimal due to the poor shape and grading of the aggregate.

In another application, a two-lane CRCP was built in Blacksburg, Virginia, as part of the Virginia Smart Road.²⁰ A total of 2247 ft (685 m) of pavement was placed. The mixture contained 35% slag as shown in Table 8. Number 57 coarse aggregate with 1 in. (25 mm) maximum size was used. The w/cm was low, 0.40, to achieve a high early strength since the contractor wanted trucks on the pavement in 7 days to allow construction of the adjacent lane. The strengths given in Table 7 indicate high flexural and compressive strengths. The permeability values were very low.

Slag cement in pavements resulted in satisfactory workability and strength and durability based on lab results and initial exposure. In the Smart Road project, the flexural strengths at 28 days were much higher than the 650 psi (4.5 MPa) specified and exceeded 1000 psi (6.9 MPa). This confirms the high ultimate strengths are attainable in concretes with slag cement.

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Mass concrete

After the early success in achieving high strength and low permeability, work on HPC was extended to temperature control in mass concrete and to high workability. Temperature rise is always a concern in mass concrete. Specifications generally set a maximum temperature and a maximum differential between the core and the surface. Generally, limits are 160°F (71°C) for the maximum temperature and 35°F (20°C) or 40°F (22°C) for the temperature differential. Based on a thermal analysis considering the reinforcement in the bridge footings on I-895, VDOT approved a maximum temperature of 170°F (77°C). The footings averaged 730 yd³ (21 m³), but the two footings in the river crossing were much larger with each having about 4000 yd³ (113 m³) of concrete. The minimum cementitious material was 565 lb/yd³ (335 kg/m³) and the maximum *w/cm* was 0.49. The minimum 28-day compressive strength was 4350 psi (30.7 MPa). To reduce the heat rise, the designers replaced 75% of the portland cement with slag. Preliminary testing indicated that the strength development was slow at room temperature; however, greater and more satisfactory strengths were achieved at higher temperatures, as shown in Figure 6. During placement, even in hot weather, the temperature was kept below 160°F (71°C) and the differential temperature within 40°F (22°C) with the high amount of slag cement, as shown in Figure 7. Specified strengths were attained at 28 days and in some cases at 7 days due to high temperature. Permeability values measured from 2 cylinders were 561 and 840 coulombs.

VDOT's successful use of high slag cement in mass concrete indicates that temperature rise can be controlled to acceptable levels, thus avoiding cracking and damage to the structure. A cold environment delays setting and strength development, but a hot environment accelerates setting and strength development. In mass concrete applications, to determine the strength development, temperature-matched curing or maturity methods should be used since standard curing temperatures do not simulate the actual environment in which higher temperatures that accelerate the strength development are encountered.

CONCLUSIONS

Concrete containing slag cement has been successfully used in transportation facilities in Virginia since mid 1980s and has become an important component of VDOT's HPC program. Slag concrete provides:

- *Low permeability.*
- *High resistance to ASR at appropriate replacement rates depending on the alkali contents.*
- *High strength at later ages but reduced early strength development especially in cold weather.* Hot weather accelerates strength development. In cold weather, smaller replacement rates can be used. If permeability is not low enough, the addition of other pozzolanic material such as silica fume in small amounts would improve permeability and durability
- *Temperature control in mass concrete, especially when used in large replacement rates.* In such applications, temperature-matched curing or the maturity method should be used to simulate the conditions of the elements.
- *Improved workability and high flowability for successful placement of members.*

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Table 1—Properties of slag concrete for Rte. 143 substructure

Test	Batch 1	Batch 2
Compressive strength, psi		
14 days	4590	4110
28 days	5940	5540
56 days	6020	6050
Flexural strength, psi		
28 days	700	685
Permeability, coulombs	1870	3000

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

The permeability specimens were moist cured for 2 weeks and then air-dried for 6 weeks.

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Table 2—First HPC structure on Route 40

Material, lb/yd ³	Substructure	Deck
Cement	352	329
Slag	235	329
Coarse aggregate	1773	1773
Fine aggregate	1254	1173
Water	259	263
Test (28 days)		
Compressive strength, psi	5930	8710
Permeability, coulombs	1094	778

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

The permeability specimens were moist cured 1 week at 73°F (23°C) and 3 weeks at 100°F (38°C).

Table 3—Lightweight concrete for Route 106 bridge beams

Material, lb/yd ³	Amount
Cement	451
Slag	301
Coarse aggregate LW	696
Coarse aggregate NW	605
Fine aggregate LW	390
Fine aggregate NW	541
Water	255
Test	
28-day compressive strength, psi	8100
1-year permeability, coulombs	916

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

Table 4—Arch bridge with SCC

Material, lb/yd ³	Amount
Cement	488
Slag	262
Coarse Aggregate	1451
Fine Aggregate	1451
Water	279
Test (28 days)	
Compressive strength, psi	7510
Permeability, coulombs	1229

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

The permeability specimens shown in this table and the following tables were moist cured 1 week at 73°F (23°C) and 3 weeks at 100°F (38°C).

Table 5—SCC test beams

Material, lb/yd ³	Amount
Cement	480
Slag	320
Coarse Aggregate	1430
Fine Aggregate	1430
Water	267
Test (28 days)	
Compressive strength, psi	8570
Permeability, coulombs	642

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa

Table 6—Ternary system of PC, fly ash, and slag cement

Material (lb/yd ³)	Amount
Cement	318
Class F fly ash	159
Slag	159
Coarse Aggregate	1755
Fine Aggregate	1101
Water	286
Test (28 days)	
Compressive strength, psi	5016 (305)
Permeability, coulombs	391 (72)

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa

Test data are an average of 31 sublots. The standard deviation is in parenthesis.

Table 7—I-64 pavement

Material, lb/yd ³	NMS 2-in	NMS 1-in
Cement	375	395
Slag	160	169
Coarse Aggregate	1935	1840
Fine Aggregate	1171	1217
Water	242	250
Test (28 days)		
Compressive strength, psi	4530	4620
Flexural strength, psi	670	685
Permeability, coulombs	1774	1672

Note: NMS: nominal maximum size aggregate; 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa

Table 8—Smart road pavement

Material, lb/yd ³	Amount
Cement	384
Slag	206
Coarse Aggregate	1795
Fine Aggregate	1267
Water	236
Test (28 days)	
Compressive Strength (psi)	7260
Flexural str (psi)	1055
Permeability (coulombs)	611

1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa

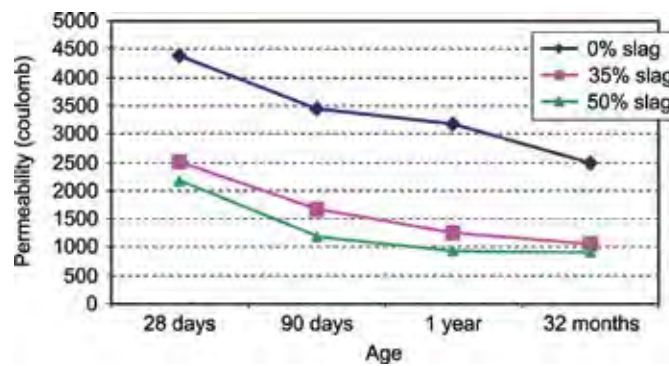


Fig. 1—Reduction in permeability with age. The w/cm was 0.45.

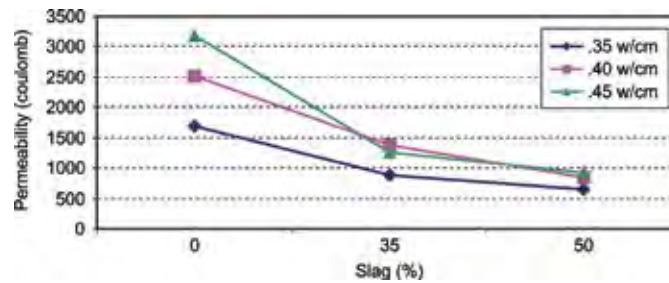


Fig. 2—Permeability of concrete with different percentage of slag for various w/cm . Test age is 1 year.

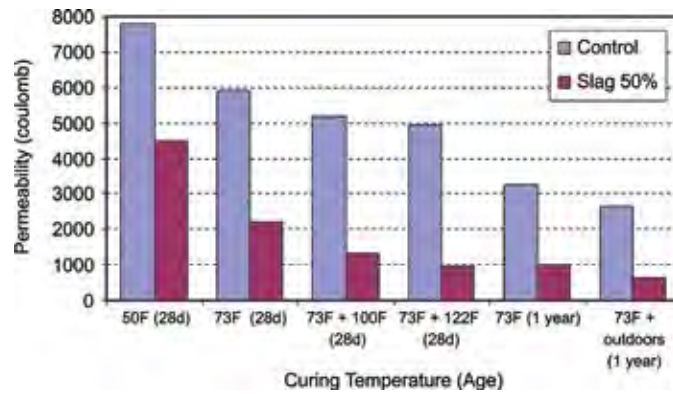


Fig. 3—Effect of temperature on permeability for w/cm of 0.40. For combined temperatures, samples cured at 73°F for 1 week and then at the higher temperature for 3 weeks or outdoors for a year. (Test age in parenthesis.)
 $T^{\circ}C = (T^{\circ}F - 32)/1.8$.

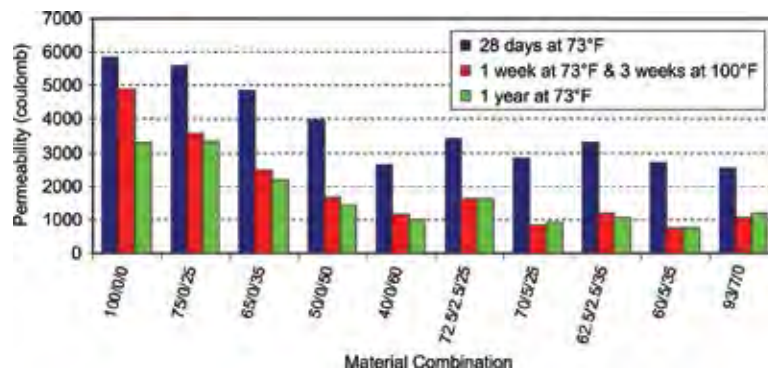


Fig. 4—Permeability of binary and ternary systems. Material combination is portland cement/silica fume/slag cement.
 $T^{\circ}C = (T^{\circ}F - 32)/1.8$.

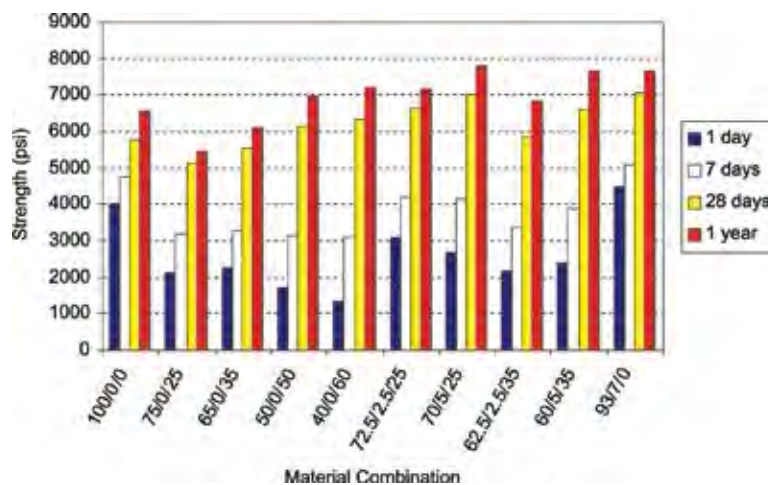


Fig. 5—Compressive strength of binary and ternary systems. Material combination is portland cement/silica fume/slag cement. 1 psi = 6.89 kPa.

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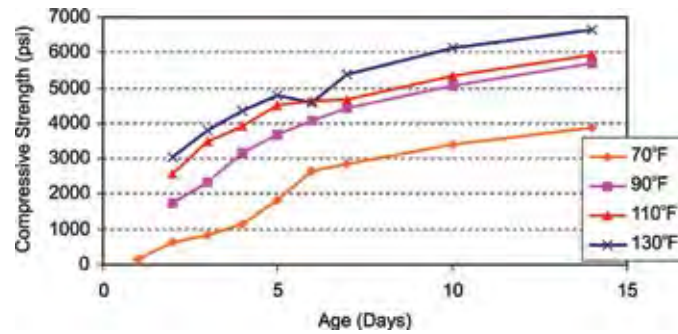


Fig. 6—Effect of temperature on the compressive strength development for mass concrete. 1 psi = 6.89 kPa;
 $T^{\circ}\text{C} = (T^{\circ}\text{F} - 32)/1.8$.

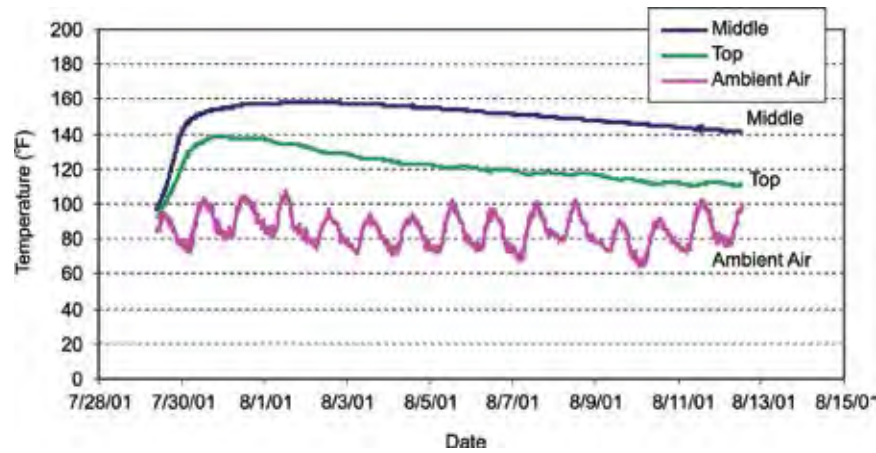


Fig. 7—Temperature development in a large footing. $T^{\circ}\text{C} = (T^{\circ}\text{F} - 32)/1.8$.

Case Studies—North American Mass-Concrete Projects Featuring ASTM C989 Slag Cement

by M.D. Luther, P. Bohme, and W. Wilson

Synopsis: This paper is a collection of over 30 brief case studies about mass-concrete projects using ASTM C989 (AASHTO M302), or similar, slag cement (formerly called ground granulated blast-furnace slag)—undertaken to learn more about concrete mixtures and considerations as they are applied in the field. With the exception of some ternary mixes, generally, the slag cement amounts equaled or exceeded the amounts of Portland cement employed in the mixtures. The information showed that a broad spectrum of proportions featuring slag cement of all grades have been used to achieve desired mass-concrete properties and outcome, including staying under a maximum core temperature, holding within a maximum differential temperature, and achieving specified strength.

Keywords: compressive strength; mass concrete; temperature; slag cement.

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INTRODUCTION

ACI 233R-03 reports that slag cement can be an effective means of controlling temperature rise in mass concrete.¹ This paper is a collection of over 30 brief case studies about projects using ASTM C989 (AASHTO M 302) slag cement (formerly called ground granulated blast-furnace slag) in mass concrete. This work was undertaken to learn more about concrete mixtures and considerations as they are applied in the field. Although temperature-history charts were available for some of the projects (Fig. 1), the scope of this paper is limited to mix design proportions and properties, casting dimensions, specified strength and temperature limits, and specified temperature differentials.

ACI 116R-00 “Cement and Concrete Terminology”² defines mass concrete as follows: “**concrete, mass**—any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking.” This definition does not state a specific minimum dimension. So, in his paper, when a casting presents at least a 0.9 m (3 ft) length in all of three dimensions, mass-concrete considerations apply. Some somewhat thinner slabs or walls are still considered to be mass concrete, because the thermal component of shrinkage and cracking was a concern addressed, at least in part, with slag-cement concrete.

USA SLAG-CEMENT SPECIFICATIONS AND GRADES

Specification ASTM C989-05³ (AASHTO M 302) describes three slag cement “grades”—80, 100, and 120 (Table 1). In general, for a specific granulated blast-furnace slag (i.e., granule) source, the higher the slag grade, the finer the slag cement has been ground.

GRADE 100-EQUIVALENT CANADIAN EXPERIENCES

During the last half of the 1980s and the early 1990s in Canada, a Grade-100-equivalent material (Table 2) was used in mass-concrete projects, several of which are described below.

Magpie Dam—The Ontario Magpie Dam stilling basin side walls were cast with 50%, by mass (typical hereafter) slag-cement concrete in 1987, in part to achieve alkali-silica reaction resistance with use of known-to-be-reactive aggregate. Although above the foundation the sidewall was less than 0.9 meter (3 ft) thick, such extensive elements present thermal challenges. Concrete was cast in the colder months with no delays, and wooden forms were employed. A 10-year inspection revealed the concrete to be performing as intended.

E.B. Eddy—E.B. Eddy Forest Products, Ltd. of Espanola, Ontario, constructed a suspended concrete inertia-block foundation for a 13,600 kg (30,000 lb) lathe in 1988. Nominal dimensions for the block were 2.4 m wide by 2.4 m high by 9.8 m long (8 ft x 8 ft by 32 ft). The block was cast in a single nominal 58 m³ (76 yd³) placement. The concrete was discharged onto wooden chutes into the form, consolidated with internal vibrators, and bull floated. Curing employed ponded water under wet burlap. Key proportioning and properties information for the 75% slag-cement mixture are shown in Table 3. The project contractor was P.B. Rombough, Ltd.; the engineer was Trow Ontario, Ltd.; and the concrete supplier was Rainbow Concrete Industries, Ltd.

Rio Algom Quirke II Leach Dams—Through the late 1980s, Rio Algom, Ltd., of Ontario, constructed a series of underground 75% slag-cement concrete dams to contain water used to leach uranium from low-grade ore. Each dam was nominally 3.7 m high by 10.7 m wide by 1.2 m thick (12 ft by 35 ft by 4 ft) and required a 47 m³ (62 yd³) monolithic casting. The specified concrete properties, all of which were achieved, were 30 MPa (4350 psi) at 28 days compressive strength, 4 to 8% air content, and 200 mm (8 in.) maximum placement slump. Key characteristics of the concrete mixture are presented in Table 3. The Rio Algom, Ltd. Engineering department designed the dams, and Rainbow Concrete Industries, Ltd., of Elliot Lake, Ontario, supplied the concrete.

Denison Mines Leach Dams—In the late 1980s, Denison Mines, Ltd., of Ontario, built a series of underground dams to retain water for leaching uranium from low-grade ore. The dams each used 40 m³ (52 yd³) of 50% slag cement concrete. The concrete design properties included 35 MPa (5080 psi) 28-day compressive strength, 5-8% air content, and a maximum slump of 152 mm (6 in.). Selected characteristics of the concrete, and two other mixtures that were evaluated, were as shown in Table 3. The dams were designed by the company engineering and construction department, and the concrete supplier was K.J. Beamish Construction Co., Ltd., of Elliot Lake, Ontario.

SLAG CEMENT MASS CONCRETE IN THE USA

Several mass concrete projects from the USA are described below. Representative chemistries of the slag cements are presented in Table 2, and a typical example of a temperature-time chart from an instrumented mass-concrete element is shown in Fig. 1.

ASTM C186⁴ work by the authors in 1995 (Fig. 2), using a cal/g maximum limit for heat generated by the 7-day age, suggested that 50 to 75%, by mass, of Grade 100 slag cement was an optimum range for a first mass-concrete mixture trial batch. The 70% amount represented a conservative approach—one that tended, also, to achieve similar 28-day strength as a comparable 100% portland-cement concrete mixture. Many of the projects described in this paper started with a 70% initial-trial-batch-mixture concept, then adjusted the slag-cement amount in response to other project considerations.

Wabasha Street Bridge—Spanning the Mississippi River at Minneapolis-St. Paul, Minnesota, the Wabasha Street Bridge employed Grade 100 slag cement in the pier foundations and stems (Fig. 3). The mass concrete construction began in late 1996, and the bridge opened in 1998. The pier foundation mixture featured 75% Grade 100 slag cement with Type II portland cement. The pier stems used a 65% slag-cement mixture. All told, approximately 7340 m³ (9600 yd³) of slag-cement concrete was used in the piers, and the key concrete characteristics are presented in Table 4.

The specified peak temperature was 71°C (160°F). The results ranged from 5°C (10°F) lower to 1°C (2°F) higher. The specified maximum temperature differential was 28°C (50°F), and the maximum recorded thermal gradient was 34°C (62°F). No cracking occurred, and part of this favorable outcome lies with the effective use of ponded water and insulation that was applied when needed. The 27.6 MPa (4000 psi) specified 28-day compressive strength was achieved for both mixes (Table 4). The 28-day-to-56-day cylinder-strength gain for the pier stem mix was from 27.7 to 31.9 MPa (4010 to 4630 psi, the range of the results, typ.) to 32.9 to 38.3 MPa (4770 to 5550 psi)—an average increase of roughly 19%.

The segmental-bridge structure was owned by the Minnesota Department of Transportation (MnDOT), and both MnDOT and US Army Corps of Engineers personnel were involved in the project. Frigg Engineers, of Tallahassee, Florida completed the structural design; Lunda Construction Company, of Black River Falls, Wisconsin won the construction contract; and concrete was supplied by CEMSTONE.

Rock 'N' Roll Hall of Fame and Museum—Concrete placements for The Rock 'N' Roll Hall of Fame and Museum began in 1993, and the building opened in spring, 1995. The structure is located in the Cleveland, Ohio north-coast harbor, which opens into Lake Erie.

Over 12,800 m³ (16,700 yd³) of white architectural slag-cement concrete was used in the structure. Originally planned to use white portland cement, white concrete was achieved with combinations of light-gray portland cement and Grade 120 slag cement. The largest single mass-concrete element was the nominal 1500 m³ (2000 yd³) 3 m thick (10 ft thick) foundation that lay in the harbor and that supported the 51 m high (168 ft high) tower. The foundation was about 19 m (62 ft) square in plan view. Some of the mass-concrete characteristics are shown in Table 4.

The museum architect was Pei Cobb Freed & Partners; the structural engineer was Leslie E. Robertson Associates; the construction managers were Turner Construction Co., Colejon Corporation, Choice Construction Co., and Bradley Construction Co.; and the concrete supplier was Cuyahoga Concrete.

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Sylvan Lake Dam Stilling Basin—Sylvan Lake Dam is located near Rome City, Indiana, which is in the northeast part of the state near Goshen. In 1995, the stilling basin to the dam was razed and rebuilt larger. The basin featured side walls bearing on mass-concrete foundations. All the concrete in the new stilling basin concrete featured a 75% amount of Grade 100 slag cement. The truck-mixed concrete was manufactured about 40 minutes from the site.

Initially concrete was crane bucketed to the forms. Later, the concrete was pumped, and the aggregate proportions were adjusted to optimize pumpability. Many of the castings employed monolithic placements of 360 m³ (600 yd³) or more. All told, over 5350 m³ (7000 yd³) of slag-cement concrete were used in the stilling basin. The concrete mixture featured 222 kg/m³ (375 lb/yd³) of slag cement, had a total cementitious materials content of 297 kg/m³ (500 lb/yd³), and used a nominal 19 mm (3/4 in.) limestone coarse aggregate. A 35% slag cement mixture was also used in grout for some sidewall anchors. The concrete supplier was Eagle Ready Mix, of Goshen, Indiana, and the contractor was Reith Riley, of the South Bend, Indiana area.

Heron Hill Reservoir—Part of the Pittsburgh Water Authority system, Heron Hill Reservoir (Fig. 4) is carved into the top of a hill about two miles north of downtown Pittsburgh, Pennsylvania. Historically, when the reservoir needed to be repaired it first had to be drained, and this impaired optimal water-system function within the city. To allow the draining of only half the reservoir at a time—thereby preserving function in the other half—in 1995 a massive wall was erected to divide the reservoir into two equal pools.

The foundation sections of the wall each employed about 380 m³ (640 yd³) of mass concrete. All told, 5350 m³ (7000 yd³) of mass concrete were required for the project. This limestone-coarse-aggregate concrete was supplied by Frank Bryan, Inc., from the South-Side plant which was located about 20 minutes from the site. The concrete mixture for the mass concrete elements (foundation and wall) featured 65% Grade 100 slag cement. To expedite placement rate, concrete was delivered into the forms simultaneously from truck chutes and a concrete pump.

Each mass-concrete foundation section was nominally 2.1 m high, 6 m wide, and over 36.5 m long (7 ft by 20 ft by over 120 ft). After completion, these in-series segments connected one side of the basin to the other. The wall, which was cast after the foundation elements were several days old, was approximately 3 m (10 ft) thick at the base and level at the top with the top of the basin rim—an estimated 6 m height (20 ft). Portions of the top sections of the reservoir concrete liner were replaced with slag-cement concrete, also.

Temperature sensors were installed in critical locations of selected mass-concrete placements by the concrete supplier. A typical example of the temperature information collected is as follows: ambient temperature at concrete placement was 4 to 10 °C (40 to 50 °F), initial concrete temperature was 21 to 24 °C (70 to 73 °F), maximum cast-element temperature was 73 °C (163 °F), and its maximum differential temperature was 22 °C (39 °F). To maintain the differential temperature below the desired 22 °C (40 °F), thermal blankets were placed on the top of each foundation element at about the 30-hour age.

Westinghouse Bettis Reaction Structure—Westinghouse Bettis is a nuclear power research facility located in the Pittsburgh, Pennsylvania metropolitan area. The facility has designed and developed nuclear reactors for, mostly, submarines and surface ships, since the 1940s. An expansion of part of the research facility was needed. In 1995 the expansion was built, and it featured a massive reaction (reaction, here, meaning resisting force.) structure. The element was congested with steel, and the prospect of, and consequences of, cracking were considered to be high.

A 75% Grade 100 slag-cement concrete was selected. No photography was allowed, and only general information about the concrete was made available. It was noted, however, that attention had been paid to wet curing of the concrete; some 28-day strength results exceeded 50 MPa (7000 psi); and the end result was acceptable.

The project was designed and managed by the internal Westinghouse engineering department. Construction Engineering Consultants, of Pittsburgh, conducted quality control, evaluated the concrete trial-batch mixtures. Concrete was supplied by Frank Bryan, Inc., from the South-Side plant, located about 60 minutes from the site.

Bethlehem Steel Caster Foundations—From September, 1995 to January, 1996, over 8400 m³ (11,000 yd³) of 65% slag-cement concrete was cast into foundations for a new continuous caster at the Bethlehem Steel works in Johnstown, Pennsylvania—located on the north side of downtown Johnstown. The concrete characteristics are presented in Table 4. On some placement dates, concrete was batched and staged for two hours before placement. There was no apparent loss of slump or workability associated with this practice—made possible by the extended workability of the 65% slag-cement mixture—which eliminated some truck-related logistic constraints. The contractor was F.W. Sheesley, Inc., and the concrete supplier was Sheesley Supply Co., of Johnstown, Pennsylvania.

Johnstown Air-Force Aviation Training Facility—Throughout 1996, the Johnstown Air-Force Aviation Training Facility was constructed in Johnstown, Pennsylvania. The primary structures associated with the project were a

20-m (66-ft)-high hangar for use by multiple helicopters at a time and an office building. Although slag-cement concrete was used in most of the project concrete, the mass concrete portions of the work—comprised of round caissons and the 1 m by 1 m (3 ft by 3 ft) grade beams they supported—used a 50% Grade 100 slag-cement concrete.

Several concrete mixtures were required by the project. One general-use mixture, which was called “flex-mix,” was essentially a Pennsylvania DOT AA mixture made with 30% slag cement. Characteristics of the concrete used in the caissons and grade beams were as shown in Table 4. The project was managed by the US Army Corps of Engineers and other government agencies, including the Pennsylvania Department of Transportation. The concrete was supplied by Fi-Hoff, Inc., of Johnstown, Pennsylvania.

Kennywood Park “Pitt Fall”—Kennywood Park is a popular amusement park located in the Pittsburgh, Pennsylvania metropolitan area, east of downtown. During the summer of 1996, the park installed a new ride called the “Pitt Fall”—generically referred to as a drop ride. Here, a car carrying about 30 thrill seekers is hauled vertically up a track to a nominal 61 m (200 ft) height. Then the car is released abruptly, allowed to free fall, and it is stopped by the time it reaches the starting point. Needless to say, large forces are transmitted to the earth by this ride.

The foundation of the Pitt Fall was comprised of a monolithic mass-concrete casting, about 6.1 m (20 ft) thick, square in the horizontal dimensions, and that used over 382 m³ (500 yd³) of mass concrete containing 65% slag cement. The initial concrete temperature was reduced with ice-chilled batch water. Internal and external temperature monitoring of the foundation was conducted by the concrete supplier. The results indicated that the peak temperature was 65°C (150°F). Although the greatest temperature differential mildly exceeded 19°C (35°F)—attributed to a failure to use thermal blankets or any other measures [after concrete placement] to control temperature—an acceptable outcome was achieved. The concrete was supplied by Frank Bryan, Inc.

Wright-Patterson Air-Force Base—Wright-Patterson Air-Force Base is located in Dayton, Ohio. Work conducted in spring of 1997 required approximately 229 m³ (300 yd³) of mass concrete. Initially envisioned was a mass-concrete mixture containing fly ash of a combination historically used in the area. Ultimately, and on short notice that precluded mixture optimization, concrete featuring 309 kg/m³ (520 lb/yd³) of cementitious materials, with a 65% amount of Grade 100 slag cement was approved and used. This development was motivated by a combination of events, including constraints on the supply of some other cementitious materials, recent favorable slag-cement mass-concrete experience on the part of a consulting engineer, and favorable slag-cement concrete experience on the part of the concrete producer.

The specified 28-day compressive strength of the air-entrained concrete was 27.6 MPa (4000 psi). The concrete was cast in three more-or-less equal sections of 76.5 m³ (100 yd³) each. The average 28-day strength was 30.1 MPa (4360 psi). The strength was acceptable. That it was somewhat lower than typically seen with other slag-cement mixtures in the area was attributed to cool weather.

Machine Base—Sekley Industries, Inc.—On May 28, 1996, D.W. Dickey and Sons, Inc. supplied truck-mixed mass concrete for a machine base at Sekley Industries, Inc. in Salem, Ohio. The 65% slag-cement concrete proportions performance results are shown in Table 5. The contractor was Hively Construction Company, Inc., of Canfield, OH.

Machine Base—Rance Industries, Inc.—On December 9, 1997, a nominal 12.2 m long by 4.6 m wide by 1.7 m deep (40 by 15 by 4-1/2 ft) machine base was cast at Rance Industries, Inc. in the Columbiana Industrial Park, Columbiana, Ohio. The 84 m³ (110 yd³) of truck-mixed concrete was supplied by D.W. Dickey & Sons, Inc. which had a concrete plant in the city. The 65% slag-cement concrete properties and performance information were well documented, and key information is presented in Table 5. The contractor was Medved Builders, of Leetonia, Ohio.

Caissons—Cartersville & Covington, GA; Lacrosse, WI—In late 1999, two Holcim (US) Inc. terminal silo-capacity expansion projects began. The company engineering specification had just been upgraded to include some previously omitted materials, including slag cement. The 35:65 portland cement:slag cement combination of cementitious materials was selected.

The Cartersville, Georgia (Fig. 5) terminal expansion mass concrete featured, in part, nominal 1.5 m (5 ft)-diameter caissons that became pier stems above ground. These would support cement silos. The concrete used Type II portland cement and a 368 kg/m³ (620 lb/yd³) total cementitious materials content. The specified compressive strength was 27.6 MPa (4000 psi) at 28 days. The average 28-day strength was 43.7 MPa (6330 psi), with the highest cylinder-pair result exceeding 55.2 MPa (8000 psi).

The Cartersville project was conducted in the winter, and the night temperatures hovered near freezing and just below on occasion. The caissons were instrumented to monitor the interior and surface temperatures. Peak temperatures occurred during the second day, and were often in the low 70s°F (70°F = 21°C). During the third mass-concrete placement, the largest interior-exterior differential temperature was 9°C (17°F), which also occurred on the second day (Fig. 1).

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Soon after the Cartersville project, the Covington, Georgia terminal silo expansion project was completed. Then, a year later, another such project was completed in Lacrosse, Wisconsin. Both of these projects employed ready-mixed concrete similar to the one used in Cartersville. Even in the cold weather placements of winter, the concrete mixture allowed for normal form removal, and the strengths always exceeded the 27.6 MPa (4000 psi) specified compressive strength.

Smart Highway Bridge Pier Foundations—The nominal 800 m (1/2 mi) long, 55 m (180 ft) high Smart Highway Bridge was built in Christianburg, Virginia in 2000 by the Virginia Department of Transportation. The first two pier foundations did not use slag cement concrete and showed cracking. At the time, the Virginia DOT specification only allowed up to a 50% slag cement dose. So, a 377 kg/m³ (635 lb/yd³) 50% Grade 100 slag cement mixture was developed and used in subsequent pier foundations castings, and the project proceeded thereafter without cracking incident. The 28-day compressive strength of the mass-concrete mixture was 39.0 MPa (5700 psi). Also, once slag cement was at the concrete producer, portions of the 55.2 MPa (8000 psi) pier-stem concrete—which was also de-facto mass concrete—were switched to a 68:32 portland cement:slag cement mixture, which achieved nearly 82.8 MPa (12,000 psi). After the Smart Highway Bridge job, Virginia DOT increased the allowable slag cement amount to 70% for mass concrete. A 30% slag cement concrete was used in the highway pavement concrete.

Holly Hill Cement Dome—In 1998-2000 a 90,000 metric ton cement storage dome was constructed at the Holcim cement plant near Holly Hill, South Carolina. Portions of the foundation and lower parts of the dome shell qualified as mass concrete. Ultimately, a 50:50 combination of Type I portland cement with a Grade 100 slag cement was selected as the dominant mixture for the project, in part, because this one mixture could be used in several applications.

Creve Coeur Lake Memorial Park Bridge—On the west side of the St. Louis metropolitan area, the 724 m (2675 ft) long variously named Creve Coeur Lake Memorial Park Bridge is part of the Page Avenue Extension project which began in 1999 and opened for traffic in October, 2003. Casting of the pier foundations and the pier stems began in late 1999 and continued into mid 2000. The structure is owned by Missouri Department of Transportation, the engineer was Jacobs Civil Inc., and the contractor was Walter Construction Corporation. Concrete for the pier foundations and stems was supplied by Breckenridge Material Company.

Historically, in the area for such mass concrete placements an 80:20 portland cement:fly ash combination had been used. For the mass concrete a Type IV portland cement was originally specified, with an intent to achieve a maximum 50 cal/gm heat in the cementitious materials components of the concrete mixture. Ultimately, a 30:70 combination of Type I/II portland cement with Grade 120 slag cement was used, and this was the only combination of materials tested—only Grade 120 slag cement was available—that achieved the stated low-heat target. All other aspects of applicable Missouri DOT specifications were engaged throughout the project.

The pier foundations were 22 x 11 x 4 m (72 x 35 x 13 ft) deep. Atop each foundation were constructed four nominal 9 m (30 ft) high the square-cross-section pier stems. After matched-temperature cylinder curing was employed, the desired compressive strength results were achieved. Each casting required several hundred cubic yards of concrete to be cast into several tight reinforcing-steel grids. Plastic settlement in the tall castings was addressed with re-vibration. One crack occurred in the hardened concrete, and this was attributed to a form feature. There was concern initially about random green/blue colorations on vertical pier stems surfaces after the forms were removed. As anticipated, these colorations matured to an even white color.

Express Parking Structure—On February 26, 2000 a nominal 1682 m³ (2200 yd³) of 70% slag-cement concrete was cast in a monolithic foundation at the southeast corner of Pennsylvania Street and Market Street in downtown Indianapolis, Indiana (Fig. 6). Located one block from Soldiers Memorial Monument, which lies in the center of downtown Indianapolis, the Express Parking Structure was being expanded. The project encountered differential soil conditions. The solution involved casting a large mat foundation, covering this with a soil layer, then constructing the above-ground portions of the parking structure. The foundation was nominally 43 m (140 ft) long by 21 m (70 ft) wide by 1.8 m (6 ft) deep. There was a relatively tight grid of ~No. 10 reinforcing bars located with what would end up being a 102 mm (4 in.) top cover with 76 mm (3 in.) side cover.

On relatively short notice, a non-air 307 kg/m³ (517 lb/yd³) mixture was developed with Indiana No. 8 [i.e., 19 mm (3/4 in.)] limestone coarse aggregate and Grade 100 slag cement. Concrete was supplied by Prairie Materials Sales from one large plant, which was about 10 miles distant, for a night placement that finished just before dawn. Approximately fifty ready-mix concrete trucks were assembled, with some brought in from other plants across the state. For efficient and safe delivery, the concrete was hauled down streets cordoned off by the police. Three concrete pumps were employed for the monolithic placement. All slag-cement product was staged at the concrete plant before the job began. Table 6 shows concrete proportioning and performance details.

As a item of interest, just after 3:00 a.m. there was an alert about a severe rain storm approaching, and it was expected to hit at 7:30 a.m. There was discussion about whether the concrete should be covered. It was anticipated that the placement would be completed by 7:00 a.m., and the bleed water would be thick enough by then to protect the concrete top surface from the rain. This is what happened, and the hard concrete surface was blemish free and being used for material staging by the end of the second day.

JTM Freezer Floor—On July 19, 2003, JTM Food Group built a mass-concrete floor (Fig. 7) for what would be an enclosed automated freezer in Harrison, Ohio, which is west of Cincinnati. The floor was nominally 91 m (300 ft) long by 18 m (60 ft) wide by 1 m (39 in.)-thick and cast atop rigid polystyrene insulation. A grid of No. 8 reinforcing bars on 304 mm (12 in.) centers was located in the bottom 0.6 m (24 in.) portion of the slab, and the top 0.4 m (15 in.) was largely free of reinforcing. The concrete featured a 40:60 portland cement:slag cement mixture that was pumped using two boom trucks. All 1759 m³ (2300 yd³) of the Grade 100 mass-concrete mixture were cast in a continuous placement in a 12-h period over one night. The concrete proportions and properties are shown in Table 6.

The concrete was cured under water for two weeks. No control joints were used, which meant that some amount of cracking was expected. The resultant amount of cracking was referred to as very little, and acceptable. The concrete was supplied by Harrison Concrete, and the contractor was Lithco.

Retirement System of Alabama, aka RSA Battle House Tower—In Mobile, Alabama, at the corner of Water Street and Dauphin Street, and also bordered by Royal Street and St. Michaels Street, the 35-story RSA Battle House Tower is the tallest office building in Alabama. Ultimately, the foundation was cast in one 6392 m³ (8360 yd³) placement over a 23-hour period, which began on the evening of November 7, 2003 and ended on Saturday the 8th (Fig. 8). A nominal 3.3 m (7 ft 6 in.) thick mat foundation was used with a two-way upper grid of large-diameter reinforcing steel. Although it was understood that a 70% slag cement mixture was technically preferred over the 60% mixture that was ultimately used, unusual local economic factors steered the mixture to the lower slag figure. Reportedly, had the temperatures been higher, the 70% mixture would have been used regardless of the other factors.

ASTM C186⁴ testing was conducted to help identify the optimum cementitious materials combination. This 7-day hydration test results are shown in Table 7. A Type I/II portland cement was used in the concrete mixture, with a blend of ASTM C33 No. 467 [50 mm (2 in.) max.] coarse aggregate with pea gravel [typically 10 mm (3/8 in.) max.]. The total cementitious content was about 285 kg/m³ (480 lb/yd³) coupled with a 0.48 w/cm. High-range water-reducing admixture was added at the concrete plant to control the slump to 150 to 200 mm (6 to 8 in.) at the placement. Because the job had been delayed into fall, no ice was needed to control the concrete temperature to under the desired 29°C (85°F) maximum. Strength was specified at 35.2 MPa (5000 psi) at 56 days, and the attained strengths were above expectation at all ages.

Air temperatures were in the 60s°F (60°F = 15.6°C), and the initial in-place concrete temperatures were in the 70s°F (70°F = 21.1°C). Based on thermocouple readings, the internal peak temperature occurred between 60 and 100 hours after placement, depending on the location of the device. The peak measured external face temperature was 44°C (112°F), and the peak internal temperature was 59°C (138°F).

The concrete was supplied by the Bayou Concrete/MMC Material, Inc./Gulf Concrete, L.L.C. organization. Among the design management companies were Skanska USA Building Inc. and Thompson, Ventulett, Stainback & Associates, Inc.

Braddock Lock and Dam Rehabilitation—Originally built in 1902, the U.S. Army Corps of Engineers Braddock Lock & Dam lay at mile 11.2 (~18 km) on the Monongahelia River, which is near Pittsburgh, PA. From 2001 to 2003 the structure was rehabilitated. The dam was replaced with two massive precast segments that were floated into place and sunk by filling with water, positioned atop the drilled-shaft foundation. A 27.6 MPa (4000 psi) at 90-day tremie concrete mixture displaced the water and filled the segments. This concrete mixture featured 15:60:22:3 of portland cement, slag cement, fly ash, and silica fume with a maximum 25-mm (1-in.) coarse aggregate. The portland cement was Type II, presenting a 7-day maximum heat of hydration of no more than 70 cal/g; the slag cement was Grade 80; and the fly ash was Class F. The w/cm was 0.38, and the compressive strengths were 12.4 MPa (1790 psi) at 7 days, 37.0 MPa (5370 psi) at 28 days, and 49.6 MPa (7190 psi) at 90 days.

A 13.8 MPa (2000 psi) at 90 days grout mixture was used under the dam. This mixture featured a 15:45:36:4 cementitious materials proportions for the portland cement, slag cement, fly ash, and silica fume. Here, the silica fume was largely used to prevent wash out during placement. The w/cm was 0.39, and the compressive strength was 5.5 MPa (800 psi) at 7 days, 28.8 MPa (4180 psi) at 28 days, and 5530 psi at 90 days.

After the project was authorized in 1992, the concrete mixtures used in the project were developed over a nine-year period with several communications per year between the local Corps personnel and materials suppliers. A

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Grade 80 slag cement was available, so the Corps used it.

Table Rock Lake Auxiliary Gated Spillway—The Table Rock Lake Auxiliary Gated Spillway, near Branson, MO upgraded the capacity of the existing dam. For the mass concrete, a 33:33:34 portland cement:slag cement:fly ash concrete was used. The portland cement was a Type II with no low-heat requirement. The slag cement was a Grade 100, and the fly ash was a Class F. The specified compressive strength was 20.7 MPa (3000 psi) at 90 days. A 75-mm (3-in.) coarse aggregate was used with a 0.49 w/cm . The structural concrete used a 34.5 MPa (5000 psi) specified compressive strength, 19 mm (3/4 in.) coarse aggregate, 0.40 w/cm , and a 61:26:13 percent by volume portland cement:slag:fly ash combination.

Maumee River Crossing [Bridge]—Crossing the Maumee River just upstream of an existing bridge and just south of Toledo, Ohio, the new Maumee River Crossing bridge featured at least two kinds of mass concrete, among the other concrete mixtures, which included pre-cast and cast-in-place elements. Cast-in-place caissons were excavated deep enough to reach bedrock, which often was between 24 m (80 ft) and 43 m (140 ft) below ground level at the river bank. These were most commonly cast with a 50:25:25 by-mass combination of portland cement, Grade 100 slag cement, and Class C fly ash. All other parts of the bridge used slag cement in the concrete, including the precast elements.

Then, the pier (called a pylon on the job) of this cable-stayed bridge needed a high-strength concrete mixture [69 MPa (10,000 psi) was specified] that was also capable of performing well for this mass-concrete application. For the 69 MPa (10,000 psi) concrete, a portland cement, slag cement, and silica fume mixture was initially considered, and a 50:50 portland cement:slag cement combination was selected. The concrete used Type I portland cement with Grade 100 slag cement, a 0.32 w/cm , 641 kg/m³ (1080 lb/yd³) of ASTM C33 No. 67 [nominal 19 mm (3/4 in.)] coarse aggregate, 344 kg/m³ (580 lb/yd³) of No. 8 [nominal 10 mm (3/8 in.)] coarse aggregate, and 682 kg/m³ (1150 lb/yd³) of fine aggregate.

Caisson casting began in mid-2002, and the high-strength work began in late 2003. The bulk of the concrete was supplied by the Stansley Group. The bridge is owned by Ohio Department of Transportation.

Atlanta, Hartsfield-Jackson International Airport Tower—In September, 2003, construction began on the Hartsfield-Jackson International Airport Tower, which, at 121-m (398-ft) tall, was the tallest in the world when completed. The 9 m (30 ft) by 9 m (30 ft) tower shaft rested on a mass-concrete mat. The 41.4 MPa (6000 psi) mass-concrete mixture featured a 51:29:20 portland cement:slag cement:fly ash combination, using Grade 100 slag cement and Class C fly ash. The w/cm was 0.40, achieved with high-range water-reducing admixture.

The 3.4 m (11 ft) thick concrete mat foundation was cast in November and December, 2004, employing over 1223 m³ (1600 yd³) of concrete. The mat-concrete slump averaged 124 mm (4.9 in.), the 7-day strength averaged 26.6 MPa (3850 psi), and the 28 day strength averaged 47.0 MPa (6810 psi). The as-measured air content was in the 3-5% range. Internal concrete temperatures ranged from 46°C (114°F) to 68°C (155°F), depending on the specific location. The concrete supplier was Allied Ready Mix.

Newtown Creek Waste-Water Facility—The City of New York Department of Environmental Protection upgraded the Newtown Creek Waste Water Facility to stay current with new Federal Guidelines. The 2003-2004 portion of this project included several massive digester tank foundations, which, all told, summed to over 38,200 m³ (50,000 yd³) of 70% slag-cement concrete. The specified compressive strength of the mass concrete was 27.6 MPa (4000 psi). The total cementitious materials content was 362 kg/m³ (610 lb/yd³), and a Grade 120 slag cement was available and used. The average compressive strength was 17.9 MPa (2600 psi) at 7 days and 39.3 MPa (5700 psi) at 28 days. The high-sulfate resistance of the slag-cement concrete was a desired property on this project.

Other—In a novel case in the mid-1990s, a concrete producer in northern Indiana supplied a 25% Grade 100 slag cement mixture for a high-early strength mass-concrete slab application exposed to an anticipated severe frost environment at a farm. The 25% slag cement dose was selected because it lay outside (on the low side) of a potential 35-55% mass-concrete exclusion range mentioned in ACI 233R. This represented an acceptable alternate approach to a mass concrete mixture, given all the considerations, and the job went well.

Some main-line paving work presents mass concrete considerations. As an example, during the 1995 Indianapolis Airport expansion, pavement as thick as 0.66m (26 in.) was cast with uniform success using a 50% Grade 100 FAA P-501-specification concrete mixture. There were at least two projects requiring several hundred cubic yards of mass concrete each in the Columbus Ohio area between 1998 and 2002. For these, the engineer would only allow Grade 80 slag cement.

In 1998, in the Dayton, Ohio area, a ready mixed concrete mis-batch resulted in two nominal four-ft-diameter caissons being cast with a 85:15 Grade 100 slag cement:fly ash (Class C) mixture. The concrete was handled and placed without other incident. One person eventually noted the whiter color of the mis-batched concrete, which

led to discovery of the situation. The engineer was informed, and the casting was kept continuously water cured. The 28-day specified strength was 31.0 MPa (4500 psi). Concrete was accepted for the caisson with strength exceeding 35.9 MPa (5200 psi).

Hanson Slag Cement (formerly Civil and Marine) used 50% Grade 120 concrete in large castings for the Cape Canaveral slag-cement plant construction, which was completed in 2004.

OBSERVATIONS AND SUGGESTIONS

1. In mass concrete, all ASTM C989 grades were used to achieve reliably specified temperature limits and compressive strength with otherwise acceptable results/outcome.
2. Type I or Type II can be used with slag cement to make mass concrete.
3. Some information (eg., Fig. 2) suggested that, for portland-cement:slag-cement mixtures, the higher the grade, the greater the slag cement percentage for optimum properties development. For an initial trial batch: for Grade 120, the 70 to 80% range is suggested; for Grade 100, the 60 to 80% range is suggested.
4. The concrete mixture is only one part of a system to address mass concrete construction. Other parts of this system include cooling the concrete materials and using thermal blankets appropriately to minimize differential temperature.
5. Relatively low total cementitious materials content mixtures should be evaluated, although, some relatively rich [for mass concrete] mixes used high slag-cement content to good effect.
6. If silo space permits, combinations of portland cement with slag cement and fly ash and/or other cementitious materials should be evaluated. These have demonstrated viability.
7. When high-early strength is needed in a mass-concrete mixture, inclusion of small amounts of silica fume may be used. Lowering w/cm represents another approach toward increasing early-age strength.

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Table 1—ASTM C989 slag grade SAI requirements, typical finenesses and SAI*

ASTM C989 Grade	ASTM C989 SAI average of last five results; requirement at 7 days	Typical as measured SAI results for midwest USA at 7 days	ASTM C989 SAI average of last five results; requirement at 28 days	Typical as measured SAI results for midwest USA at 28 days	Typical Blaine fineness for midwest USA, m ² /kg
80	No SAI requirement	65-70	75	95-105	410-490
100	75	81-92	95	106-126	460-620
120	95	95-109	115	117-145	530-650

*SAI = ASTM C989 slag activity index.

Note: 1 kg/m³ = 1.69 lbs/yd³.

Table 2—Typical slag-cement chemistry

Reported as oxides composition*	Source: Blind River, Canada [†] , %		Source: Chicago, IL [‡] , %		Source: Weirton, WV [§] , %	
	Average	S.D. [§]	Average	S.D.	Average	S.D.
CaO	41.0	1.4	38.5	1.8	37.7	1.6
SiO ₂	38.1	1.0	37.9	1.3	36.9	1.4
Al ₂ O ₃	7.1	0.3	7.9	0.6	9.6	1.1
Fe ₂ O ₃	0.9	1.3	0.7	1.9	0.6	0.3
MgO	10.4	0.5	11.7	1.4	11.8	1.1
SO ₃	0.1	0.1	0.1	0.1	0.1	0.1
S, total	1.2	0.2	1.1	0.2	1.3	0.2
Aklali ^{**}	0.6	0.1	0.7	0.1	0.7	0.2
MnO	0.4	0.1	0.8	0.2	0.7	0.3
L.O.I. ^{††}	0.5	0.4	0.4	0.4	0.4	0.4
Number of specimens	40	—	48	—	26	—

Notes: *GBFS is glass. As such, there is no CaO, SiO₂, etc. in the GBFS. The elements of calcium, silicon, oxygen, etc., exist throughout the glass. By convention, the distribution of elements is reported as oxides of these elements; [†]Data circa. 1992; [‡]Data circa. 1997; [§]S.D. = standard deviation; ^{**}(%Na₂O + 0.658) (% K₂O); ^{††}L.O.I. = loss on ignition, here, conducted in a nitrogen environment.

Table 3—Canadian job data: E.B. Eddy, Rio Algom, Denison Mines

Project	E.B. Eddy	Rio Algom	Denison Mines		
Application	Machine base	Dams	Dams		
Slag cement amount, % by mass, cmts.	75	75	0	50	65
Total cementitious, kg/m ³	401	430	476	476	476
CA size, mm	19	10	10	10	10
CA amount at SSD, kg/m ³	1080	600	594	594	594
FA amount at SSD,* kg/m ³	795	1075	~1070	1070	~1070
Water at SSD aggs., kg/m ³	184	245	—	266	—
Air-entraining admixture, mL/m ²	—	100	—	100	—
Water-reducing admixture, mL/m ²	870	1505 [†]	—	1760	—
Slump, mm	100-130	—	—	—	—
Air temperature, °C	17-22	—	—	—	—
Concrete temperature, °C	~20	—	—	—	—
Compressive strength, MPa	Lab cured	TMC [†]			
at 3 days	7.9	19.8	—	—	—
at 7 days	17.4	23.6	—	—	—
at 14 days	25.8	24.5	13.5	26.8	19.7
at 28 days	28.3	28.4	34.1	34.3	37.1
at 56 days	39.6	35.6	44.3	37.2	48.4

Notes: *The fine aggregate and coarse aggregate proportions are as shown. Some “reverse mixes” were used; [†]TMC = temperature-matched curing, wherein cylinders were cured to the same temperature as the block interior; ^aa water reducer/retarder was used. 1 kg/m³ = 1.69 lb/yd³; 1 mm = 0.04 in.; 1 mL = 0.03 oz; 1 m² = 11 ft²; °F = (°C × 1.8) + 32; 1 MPa = 0.145 ksi.

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Table 4—Job data: Wabasha Street Bridge; Rock ‘N’ Roll Hall of Fame and Museum; Johnstown, PA, Air Force Facility

Project	Wabasha Street Bridge		Rock ‘N’ Roll Hall of Fame and Museum	Bethlehem Steel	Johnstown Air Force Facility
Application	Pier foundation	Pier stem	Tower foundation	Caster foundation	Caissons and grade beams
Mix label	3A32	1A43	—	—	—
Slag cement amount, % by mass, cmts.	70	60	70	65	50
Total cementitious, kg/m ³ lb/yd ³	350 (590)	350 (590)	320 (539)	326 (549)	334 (563)
CA size*, mm (in.)	—	—	—	25 (1.00)	19 (0.75)
CA amount at SSD*, kg/m ³ (lb/yd ³)	—	—	1009 (1700)	1185 (1997)	1093 (1842)
FA amount at SSD,* kg/m ³ (lb/yd ³)	—	—	795 (1340)	759 (1279)	781 (1316)
Water at SSD aggregates, kg/m ³ (lb/yd ³)	—	—	—	163 (275)	177 (298)
w/cm	0.45	0.48	0.45	0.50	0.53
Slump, spec. max., mm (in.)	—	—	203 (8.0)	—	—
Slump, mm (in.)	—	—	—	140 (5.5)	—
Specified air, %	—	—	6 ± 1/2	—	—
Air content, %	—	—	—	6.0	—
Air temperature at plant	—	—	4-10°C (40-50°F)	—	—
initial concrete temp.	—	—	21-24°C (70-73°F)	—	—
Max. concrete temp.	—	—	73°C (163°F)	—	—
Max. differential temp.†	—	—	22°C (39°F)	—	—
f _c ¹ , MPa (psi)	27.5 (3990)	27.5 (3990)	27.6 (4000)	27.5 (3990)	—
Compressive strength					
at 7 days, MPa (psi)	—	—	—	26.2 (3800)	—
at 28 days, MPa (psi)	32.3 to 35.1 (4680 to 5090)	27.7 to 31.9 (4010 to 4630)	—	40.0 (5800)	—

Note: *CA = coarse aggregate. FA = fine aggregate. SSD = saturated-surface dry moisture condition of aggregates; †the difference between the bottom 1 m (3.1 ft) concrete layer and the top 1 m (3.1 ft) layer.

Table 5—Job data: Eastern Ohio machine bases

Project	Salem, OH	Columbiana, OH
Application	Machine base	Machine base
Slag cement amount	65%	65%
Total cementitious	297 kg/m ³ (500 lb/yd ³)	297 kg/m ³ (500 lb/yd ³)
CA size	25 mm (1 in.)	25 mm (1 in.)
CA amount at SSD	1074 kg/m ³ (1811 lb/yd ³)	1009 kg/m ³ (1700 lb/yd ³)
FA amount at SSD	875 kg/m ³ (1475 lb/yd ³)	—
Water at SSD aggs.	166 kg/m ³ (280 lb/yd ³)	122 kg/m ³ (205 lb/yd ³)
<i>w/cm</i>	0.56	0.41
Water-reducing admixture	263 mL/m ³ (15 fl oz/yd ³)	263 mL/m ³ (15 fl oz/yd ³)
High-range water-reducing admixture	1122 mL/m ³ (64 fl oz/yd ³)	1122 mL/m ³ (64 fl oz/yd ³)
Slump, before HRWRA	76 mm (3 in.)	76 mm (3 in.)
Slump, after HRWRA	203 mm (8 in.)	216 mm (8.5 in.)
Air content	0.8%	1%
Unit weight	2413 kg/m ³ (150.6 lb/ft ³)	2429 kg/m ³ (151.6 lb/ft ³)
Initial concrete temperature	—	17°C (62°F)
Cylinder high-low at 1 day ^(a)	—	22–13°C (71–55°F)
Cylinder high-low at 1 day [†]	—	18–13°C (64–55°F)
Compressive strength	152.4 mm (6 in.) diameter plastic cylinder molds	152.4 mm (6 in.) diameter plastic cylinder molds to 28 days [‡]
at 7 days	24.1 MPa (3500 psi)	28.3 MPa (4100 psi)
at 14 days	—	39.8 MPa (5660 psi)
at 28 days	41.1 MPa (5960 psi)	44.4 MPa (6440 psi)
at 56 days	43.3 MPa (6280 psi)	52.4 MPa (7600 psi)
at 112 days	50.5 MPa (7320 psi)	53.0 MPa (7680 psi)
at 188 days	51.2 MPa (7430 psi)	58.2 MPa (8440 psi)

Note: ^a152.4 x 304.8 mm (6 x 12 in.) cylinders ; [†]101.6 x 203.2 mm (4 x 8 in.) cylinders; [‡]after 28 days, 101.6 mm (4 in.) diameter cylinders were used. The reported result was divided first by 1.05, to convert the results to the larger cylinder size.

Table 6—Job Data: Express Parking Structure; JTM Freezer Floor

Project	Express Parking Structure	JTM Freezer Floor
Application	Mat foundation	Floor and foundation in one
Slag cement amount	70%	60%
Total cementitious	309 kg/m³ (517 lb/yd³)	333 kg/m³ (560 lb/yd³)
CA size [§]	19 mm (3/4 in.)	~31 mm (~1.25 in.)
CA amount at SSD	—	1063 kg/m³ (1790 lb/yd³)
FA amount at SSD	—	775 kg/m³ (1300 lb/yd³)
Water at SSD aggs.	—	168 kg/m³ (283 lb/yd³)
Water-reducing admixture	—	Was used
Average slump*	222 mm (8-3/4 in.)	178 mm (7 in.)
Air content*	1.4%	1%
Unit weight*	2381 kg/m³ (148.3 lb/ft³)	2403 kg/m³ (150.0 lb/ft³)
Time of setting (ASTM C403)		
Initial	6 h, 20 min	
Final	8 h, 40 min	
f'_c	34.5 MPa (5000 psi)	
Compressive strength**		
at 1 day†	1.1 MPa (170 psi)	—
at 1 day†	4.1 MPa (600 psi)	—
at 2 days†	3.3 MPa (480 psi)	—
at 3 days†	5.5 MPa (800 psi)	15.2 MPa (2200 psi)
at 4 days†	9.0 MPa (1300 psi)	—
at 7 days†	22.1 MPa (3200 psi)	32.6 MPa (4730 psi)
at 14 days	—	36.9 MPa (5350 psi)
at 28 days	35.9 MPa (5200 psi)	44.5 MPa (6450 psi)
at 56 days	—	52.8 MPa (7660 psi)

Note: *Before pump, and the average of six measurements between 1:15 a.m. and 4:45 a.m.; [†]4/21/04 trial-batch results; [‡]job result; [§]limestone; and ** Fresh concrete testing and 101.6 x 203.2 mm (4 x 8 in.) plastic cylinders were cast, from concrete samples recovered from trucks leaving the concrete plant.

Table 7—RSA Battle House Tower concrete proportion development ASTM C186 results

Cementitious materials combination (portland cement:slag cement:fly ash)*	ASTM C186 results, spring 2003, conducted by Construction Technology Laboratories, Skokie, IL (calories per gram)
80:0:20	80.7
50:50:0	78.2
40:60:0	66.5
30:70:0	61.9

Note: *The portland cement was the Type I/II used on the job, from Theodore, AL; the slag cement was an ASTM C989 Grade 100 material from Birmingham, AL; The fly ash was an ASTM C618 Class C material from Miller, AL.

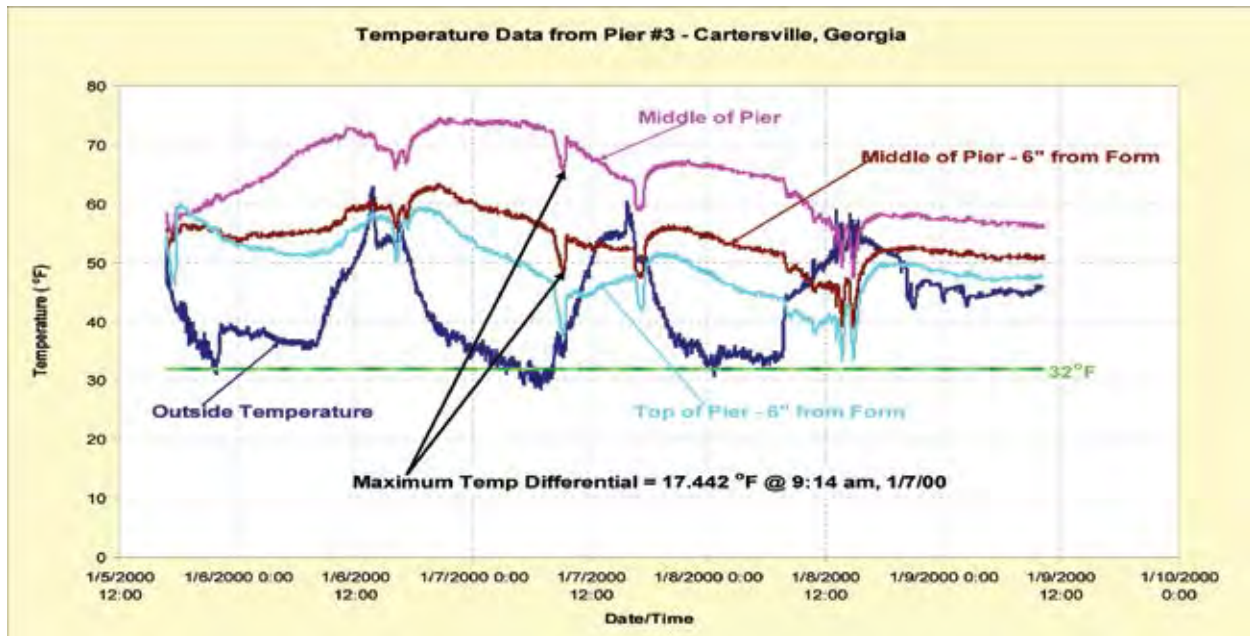
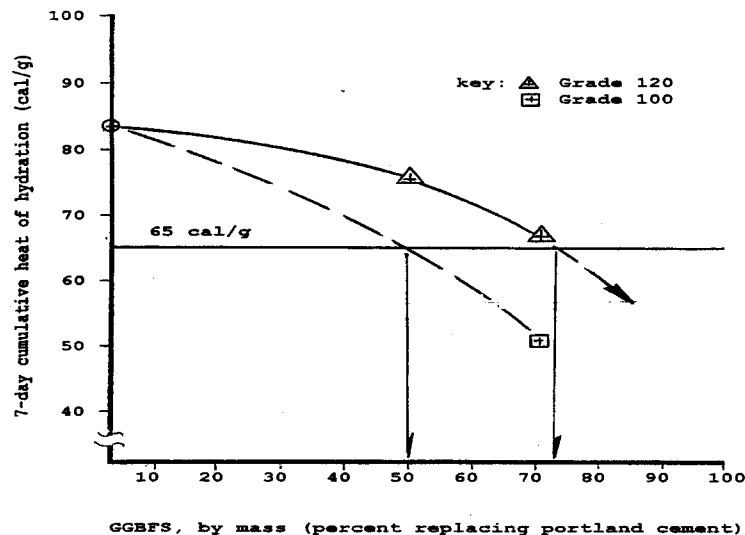


Fig. 1—Holcim (US) Inc. cement terminal expansion project, Cartersville, GA; Temperature Chart, as supplied, including units, from project personnel from the third pier casting 1/7th/2000, 65% slag cement (selected dual units: temp. differential of 17.4°F = 10°C; 6 in. = 152 mm).



Note a: These ASTM C 186-94 data were generated by Construction Technology Laboratories, of Skokie, Illinois, and transmitted to the author on Aug. 17, 1995. ASTM C 150 Type I portland cement was used. The Grade 120 GGBFS was from Pittsburgh, PA, and the Grade 100 was from Weirton, WV. The engineer's threshold of approval was 65 cal/g, which the Grade 120 GGBFS required a nominal 72% amount to achieve, and the Grade 100 required a nominal 50% amount.

Fig. 2—Effect of GGBFS amount upon heat of hydration for Grade 100 and 120 GGBFS. See note (a). (Note: 1 g = 0.002 lb.)



Fig. 3—Wabasha Street Bridge, Minneapolis-St. Paul, MN; 75% slag-cement concrete in pier foundations, 65% in pier stems; 1996-1998.



Fig. 4—Heron Hill reservoir, Pittsburgh, PA; 65% slag-cement concrete; 1995.



Fig. 5—Holcim (US) Inc. terminal expansion, Cartersville, GA; 65% slag-cement concrete; winter of 1999-2000.



Fig. 6—Express Parking Structure, Indianapolis, IN; during night placement beginning on February 26, 2000; 70% slag-cement concrete



Fig. 7—JTM freezer floor placement, Harrison, OH; 60% slag-cement concrete; night placement ending in morning, July 2003.



Fig. 8—RSA Battle House Tower, Mobile, AL; 60% slag-cement concrete; 23-h placement starting November 7, 2003.

Effectiveness of Slag Cement in Preventing Alkali-Silica Reaction: Ten-Year Results

by D.D. Higgins and G. McLellan

Synopsis: To investigate the relationship between the alkali content of concrete and the expansion caused by alkali-silica reaction, several hundred concrete prisms containing reactive natural aggregate, were regularly measured over a period of ten years. These prisms contained between 0 and 70% slag cement in combination with portland cements, and had concrete alkali contents between 4.5 and 11 kg/m³ (0.3 and 0.7 lb/ft³). The alkali content of the Portland cements ranged from 0.54 to 1.15% and that of the slag cements from 0.58 to 0.83%. Prisms were moist-stored at 20°C (68 °F) and at 38°C (100°F).

Storage at the higher temperature accelerated the rate of expansion, and slightly increased the ultimate expansion. The correlation between the two temperatures was very good in terms of classifying mixtures as either 'expanding' or 'non-expanding'. It is concluded that storage at 38°C (100°F) is an accelerated test that can be used to reliably predict what would happen at 'normal' temperature. The mixtures containing slag cement, tolerated much greater alkali contents in the concrete, without expansion. This effect was more pronounced for higher proportions of slag cement.

Keywords: accelerated tests; alkali-silica reaction; expansion; slag; slag cement.

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INTRODUCTION

Slag cement is a by-product from Iron-making. Iron blast-furnaces operate at a temperature of about 1500°C (3000°F) and are fed with a carefully controlled mixture of iron-ore, coke and limestone. The iron ore is reduced to iron and the remaining materials form a slag that floats on top of the iron. This slag is periodically tapped off as a molten liquid and then rapidly quenched in large volumes of water. The quenching optimises the cementitious properties and produces granules similar to a coarse sand. This granulated slag is then dried and ground to a fine powder, which in the US is termed 'slag cement.' In the UK it is known as ground granulated blast-furnace slag (ggbfs).

Slag cement is a cementitious material that can be used either as a within-mixer addition at the concrete mixer, or else as a component of factory-blended portland blastfurnace slag cement. Portland blastfurnace slag cement has been produced for over a hundred years and after normal portland cement, is the world's second most commonly used cement type. It has been used to construct countless concrete structures in all climates, in many places where ASR-susceptible aggregates are commonly available. Despite extensive enquiries, the authors have found no evidence or report, where any concrete structure with greater than 35% blastfurnace slag content, has suffered damage from alkali-silica reaction. The undoubted ability of blastfurnace slag to prevent alkali-silica reaction (ASR) has also been confirmed by numerous laboratory studies.¹

Regulations and advice on the avoidance of ASR vary from country to country.^{2,3} As shown in Table 1, the effectiveness of cements containing 50% or more of slag to combat ASR is well accepted but recommendations for percentages less than 50%, are not so well established. The programme of testing reported in this paper, was initiated in the UK in order to establish how to deal with lower percentages. Factory-blended slag cements are not normally available in the UK and separate slag cement is added at the mixer, commonly at a replacement level of 40 or 50%. Unlike the situation in the US where precaution against ASR is generally based on testing the mix to be used, the UK approach to ASR limits the calculated 'reactive alkali' content of the concrete. For normal portland cement, the full alkali content (expressed as the sodium oxide equivalent) is included in the calculation. Based on the 5-year results of this project⁴ and other investigations, only a fraction of the acid-soluble alkali content of the slag cement has to be taken into account, and this fraction varies with the level of slag cement:^{5,6}

- If slag cement is between 0 and 24% of cementitious: all of alkali included
- If slag cement is between 25 and 39% of cementitious: half of alkali included
- If slag cement is over 39% of cementitious: none of alkali included

Although the issues that originally prompted the research programme had been resolved by five years, it was decided to continue monitoring the specimens until they were ten years old. Ten years was considered to be sufficiently long to exclude any possibility that slag cement might be delaying damaging ASR expansion, rather than preventing it. A particular interest was to see how 'accelerated' specimens stored at 38°C (100°F) behaved relative to those stored at the 'normal' temperature of 20 °C (68 °F).

The expansion measurements were carried out on concrete prisms containing natural UK aggregates. The chosen aggregates were a combination of flint-bearing sand and crushed limestone coarse aggregate, selected because ASR damage in UK structures has resulted with this combination. The following parameters were varied:

- Cementitious content 420 to 1000 kg/m³
(26 to 62 lb/ft³)
- Percentage slag cement 0% to 70%
- Na₂O_{equiv} content of portland cement 0.54% to 1.15%
- Na₂O_{equiv} content of slag cement 0.58% and 0.83%
- Added alkali (as Na₂O_{equiv}) 0 to 3.8 kg/m³
(0 to 0.25 lb/ft³)
- Storage temperature 20 and 38°C
(68 and 100°F)
- The water content was adjusted to achieve a slump of between 30 and 50 mm
(1.2 and 2 in.)

Since an initial aim of the programme was to test a hypothesis that slag cement contributes one half of its total acid-soluble alkali to the alkali-silica reaction, the matrix of mixture designs was based on this assumption. However, a sufficiently wide range of mixtures was included to enable alternative hypotheses to be tested. Nearly three hundred specimens, corresponding to 136 different combinations of the above were monitored.

EXPERIMENTAL METHODS AND MATERIALS

Prisms [75 x 75 x 285 mm (3 x 3 x 11.2 in.)] were cast with stainless steel inserts for length measurement. Four prisms were cast from each mixture and each prism was initially measured and weighed after 24 hours. Subsequently, two of the prisms were moist-stored at $20 \pm 2^\circ\text{C}$ ($\sim 68^\circ\text{F}$) and measured at three monthly intervals, while the other pair was moist-stored at $38 \pm 2^\circ\text{C}$ ($\sim 100^\circ\text{F}$) and measured at monthly intervals. After 2 years, the time between measurements was increased, as seemed appropriate. The preparation and measurement of specimens followed the procedure that is now standardised as BS 812-123: 1999,⁷ but there was a slight difference in the storage conditions from those in this Standard. The specimens were wrapped in moist towelling or cloth, placed inside '500 gauge' polythene tubing which was sealed at each end and then wrapped with a protective plastic mesh. The wrapped prisms were stored horizontally. They were not moved around in the cabinet as required by BS 812-123 but the temperature profile across the cabinet was measured to ensure that temperature was even.

The concrete mixtures were designed to produce nominal 'reactive alkali' contents generally either 5, 6, 7, or 8 kg/m³ (0.31, 0.37, 0.44, or 0.50 lb/ft³), using three combinations of portland cement alkali contents and 2 slag cement alkali contents. It was assumed for the purpose of calculation of the 'reactive alkali' content that 50% of the acid-soluble alkali in the slag cement was available for reaction. Details of the materials are given in Table 2 and the concrete mix proportions in Table 3. Mixtures that would have required in excess of 1000 kg/m³ (62 lb/ft³) of cementitious to achieve the target reactive alkali content were made with a cementitious content of 1000 kg/m³ (62 lb/ft³) and potassium sulphate was added to bring the alkali to the required level. After the programme had commenced, it was found that the measured alkali content of some of the cementitious materials did not coincide exactly with the values originally indicated by the manufacturers. It is for this reason that the actual alkali contents of the mixtures do not always precisely align with the nominal values.

In all the concretes, 25% of the flint-bearing sand (ex Thames Valley) was included by mass of the total aggregate based on a mixture with a cement content of 700 kg/m³ (44 lb/ft³). The combination of aggregates chosen has a wide 'pessimum' and it has been separately reported that similar expansions are obtained with between 20 and 40% Thames Valley sand⁸ and with between 15 and 35% Thames Valley sand.⁹

RESULTS

The specimens were cast over a period of time and a previous paper⁴ reports the expansions when the specimens were between 4.5 and 6 years old. The smallest expansion at which cracking was detected was 0.06%, and generally the width of any cracks present did not reach 0.1 mm (0.004 in.) until the expansion was at least 0.10%. For the largest expansions, the crack widths approached 1 mm (0.04 in.). On this basis it was decided to choose 0.10% expansion as the critical criterion, below which the specimens were not considered to have suffered from ASR damage. However 0.10% expansion might be considered a little high as the critical criterion, and the results were also analysed using 0.05% expansion as the critical expansion. Table 4 shows the time taken by the mixtures to reach 0.10% expansion at 20°C (68°F) compared with 38°C (100°F). At the higher temperature, the shortest time to reach this expansion was 2 months and the longest time was about 7 years. At the lower temperature, the shortest time to reach 0.10% expansion was 9 months and the longest was about 9 years. Table 4 also shows the times to reach 0.05% expansion and the ultimate expansions.

DISCUSSION

Effect of storage temperature

Figure 1 shows the effect of the storage temperature on the time to reach 0.05% expansion. Figure 2 is a similar graph for 0.10% expansion. As expected, storage at the higher temperature accelerates ASR expansion. For the concrete mixtures that expand rapidly (those to the left of the graphs), there is a good correlation between the two temperatures, with the 0.05% and 0.10% expansions both exceeded about three times faster at the higher temperature than at the lower temperature. The mixtures that expanded only slowly (the points to the right of the graphs), also expanded faster at the higher temperature. At the right of the graphs, there is considerable scatter and it is not necessarily apparent that the 'three-times-faster' relationship also applies to the slowly-expanding mixtures. The high scatter of the slowly expanding specimens is probably due to experimental factors. For speci-

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mens only expanding by say 0.02% per year (not much greater than the repeatability of measurement), it was difficult to be precise about the age at which expansion reached 0.05 or 0.10%. Also there were problems with maintaining the specimens in a moist state over ten years, due to deterioration of the sealing materials.

Figure 3 compares the magnitude of the ultimate expansions at the two temperatures and there is a good correlation between the two temperatures, with a tendency for the ultimate expansion to be about a quarter greater at the higher temperature than at the lower temperature.

From the results in Table 4, it can be seen that if an expansion of 0.10% is taken as the critical criterion for classifying specimens as 'expanding', then those concrete mixtures that 'expand' at the lower temperature, also expand at the higher temperature. The same is true when the expansion criterion is chosen as 0.05%. On this basis it appears that storage at 38°C (100°F) will reliably identify the concrete mixtures that are going to expand when stored at 20°C (68°F) but will do so in about one third of the time required at the lower temperature. On this basis it is concluded that storage at 38°C (100°F) is an accelerated test that should reliably predict what will happen at 'normal' temperatures.

Testing at 38°C (100°F), appears to err slightly on the safe side. Storage at the higher temperature caused two of the concrete mixtures to exceed 0.10%, while equivalent mixtures stored at the lower temperature failed to achieve this expansion within the 10-year time-scale of the project. These were mixtures where the ultimate expansions at 38°C (100°F) were relatively small and only just exceeded 0.10% (mixtures '7Hh50' and '6Ml50').

Effect of slag cement

Figure 4 plots the expansion at 20°C (68°F) against the total alkali in the concrete mixture. Expansion increases with increasing alkali content, but decreases with increasing percentage of slag cement. The PC-only mixtures expanded at concrete alkali levels, as low as 5.0 kg/m³ (0.31 lb/ft³). Of particular relevance is the PC-only mixture with 458 kg/m³ (29 lb/ft³) of high-alkali cement, which exhibited a 'damaging' expansion of 0.14% at a concrete alkali content of 5.3 kg/m³ (0.33 lb/ft³): this particular mixture corresponds closely to concrete mixtures that have suffered ASR damage in actual UK structures. The mixtures with 25% slag cement had increased resistance to expansion and the lowest concrete total-alkali content to reach 0.10% expansion was 5.6 kg/m³ (0.35 lb/ft³) at a cementitious content of 595 kg/m³ (37 lb/ft³). Even greater resistance was shown by the 50% slag cement mixtures, where the lowest concrete total-alkali content to reach 0.10% expansion was 8.5 kg/m³ (0.53 lb/ft³) at a cementitious content of 856 kg/m³. None of the 70% slag cement mixtures expanded measurably at 20 °C (68 °F), even with cementitious contents of 1000 kg/m³ (62 lb/ft³) and concrete total-alkali contents of over 10 kg/m³ (0.6 lb/ft³). It is apparent from Figure 3 that concretes containing slag cement tolerate greater concrete total-alkali contents without expanding and that the effect becomes remarkably pronounced at higher proportions of slag cement. With 50% or more of slag cement, expansion only occurs with cementitious contents that are far in excess of what would normally be used.

Figure 5 plots the ultimate expansion of the specimens stored at 20°C (68°F) against 'reactive alkali' content. The 'reactive alkali' content was calculated on the basis that the portland cement and the potassium sulfate contribute all their Na₂O_{equiv}, but the slag cement only contributes half. The points for 25% slag cement are close to, but generally to the right, of those for portland cement. This indicates that the assumption that slag cement contributes half of its alkali content, is not unreasonable at 25% slag cement. However the points for higher levels of slag cement, are well to the right of those for portland cement, indicating that the 'one half' assumption is far from valid at higher levels of slag cement.

CONCLUSIONS

1. The concrete prism test produced expansion in the laboratory with a mixture similar to that known to have suffered ASR damage in the UK, in actual structures.
2. Storage of concrete prisms at 38°C (100°F) provides an accelerated test for ASR, which correlates well with storage at 20°C (68°F). All the concrete mixtures that exceeded 0.10% expansion at the lower temperature, also did so at the higher temperature.
Storage of prisms at 38°C (100°F) produced ASR expansion about three times faster than storage at 20°C (68°F).
3. There was a good correlation between the ultimate expansions. Specimens stored at the higher temperature showed slightly greater ultimate expansions than equivalent specimens stored at the lower temperature.
4. The concretes containing slag cement, tolerated greater alkali contents without expanding. This became more pronounced as the proportions of slag cement increased.

5. None of the concretes containing 70% slag cement, expanded significantly.
6. The assumption that slag cement contributes one half of its alkali was reasonably valid at low slag cement levels (25% slag cement). However at higher levels such an assumption is not appropriate.

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Table 1—ASR requirements whereby slag cements can be considered equivalent to low-alkali cement

Country	Percent slag	Maximum sodium oxide equivalent of cementitious constituent	Maximum sodium oxide equivalent of portland cement component only
Germany	>50	1.1%	no limit
	>65	2.0%	no limit
Holland	>50	1.1%	no limit
	>65	2.0%	no limit
Belgium	35 to 50	0.9%	no limit
	>50	1.1%	no limit
France	60 to 80	1.1%	no limit
	>80	2.0%	no limit
Sweden	50	1.3%*	no limit
	>65	2.0%	no limit
Japan	>40	no limit	0.8%
	>50	no limit	no limit
South Africa	>40	no limit	no limit

* There is a formula to calculate the maximum at intermediate slag levels.

Table 2—Alkali content of cementitious materials

	Sodium oxide equivalent content	
	Nominal	Measured
Portland cement 'H'	1.20%	1.15%
Portland cement 'M'	0.87%	0.87%
Portland cement 'L'	0.605	0.54%
Slag cement 'h'	0.87%	0.83%
Slag cement 'l'	0.45%	0.58%

Table 3—Concrete mixtures

Mixture	PC used	Slag used	Percent slag	Total cementitious, kg/m ³	NaO ₂ equiv from K ₂ SO ₄ , kg/m ³	Total NaO ₂ equiv, kg/m ³
5Ho	H	—	0	417	0	4.8
5Hh25	H	h	25	496	0	5.3
5Hh125	H	l	25	523	0	5.3
5Hh50	H	h	50	612	0	6.1
5Hh150	H	l	50	702	0	6.1
5Hh70	H	h	70	752	0	7.0
5Hh170	H	l	70	966	0	7.3
6Ho	H	—	0	500	0	5.8
6Hh25	H	h	25	595	0	6.4
6H125	H	l	25	627	0	6.3
6Hh50	H	h	50	734	0	7.3
6Hh150	H	l	50	842	0	7.3
6Hh70	H	h	70	903	0	8.4
6Hh170	H	l	70	1000	0.8	8.3
7Ho	H	—	0	583	0	6.7
7Hh25	H	h	25	694	0	7.4
7Hh125	H	l	25	732	0	7.4
7Hh50	H	h	50	856	0	8.5
7Hh150	H	l	50	982	0	8.5
7Hh70	H	h	70	1000	0.4	9.7
7Hh170	H	l	70	1000	1.8	9.3
8Ho	H	—	0	667	0	7.7
8Hh25	H	h	25	793	0	8.5
8Hh125	H	l	25	837	0	8.4
8Hh50	H	h	50	979	0	9.7
8Hh150	H	l	50	1000	0.9	9.6
8Hh70	H	h	70	1000	1.4	10.7
8Hh170	H	l	70	1000	2.8	10.3
5Mo	M	—	0	575	0	5.0
65Mh25	M	h	25	657	0	5.7
5M125	M	l	25	705	0	5.6

Table 3—Concrete mixtures (cont.)

Mixture	PC used	Slag used	Percent slag	Total cementitious, kg/m ³	NaO ₂ equiv from K ₂ SO ₄ , kg/m ³	Total NaO ₂ equiv, kg/m ³
5Mh50	M	h	50	766	0	6.5
5M150	M	l	50	913	0	6.6
5Mh70	M	h	70	884	0	7.4
5M170	M	l	70	1000	0.8	7.5
6Mo	M	—	0	690	0	6.0
6Mh25	M	h	25	788	0	6.8
6M125	M	l	25	847	0	6.8
6Mh50	M	h	50	920	0	7.8
6M150	M	l	50	1000	0.5	7.8
6Mh70	M	h	70	1000	0.3	8.7
6M170	M	l	70	1000	1.8	8.5
7Mo	M	—	0	805	0	7.0
7Mh25	M	h	25	920	0	7.9
7M125	M	l	25	988	0	7.9
7Mh50	M	h	50	1000	0.5	9.0
7M150	M	l	50	1000	1.5	8.8
7Mh70	M	h	70	1000	1.3	9.7
7M170	M	l	70	1000	2.8	9.5
8Mo	M	—	0	920	0	8.0
8Mh25	M	h	25	1000	0.4	9.0
8M125	M	l	25	1000	0.9	8.9
8Mh50	M	h	50	1000	1.5	10.0
8M150	M	l	50	1000	2.5	9.8
8Mh70	M	h	70	1000	2.3	10.7
8M170	M	l	70	1000	3.8	10.5
5Lo	L	—	0	833	0	4.5
5Lh50	L	h	50	966	0	6.6
6Lo	L	—	0	1000	0	5.4
6Lh50	L	h	50	1000	0.8	7.7
7Lo	L	—	0	1000	1.0	6.4
7Lh25	L	h	25	1000	1.4	7.5
7Lh50	L	h	50	1000	1.8	8.7
7Lh70	L	h	70	1000	2.2	9.6
5.5Ho	H	—	0	458	0	5.3
5.5Hh25	H	h	25	545	0	5.8
5.75Ho	H	—	0	479	0	5.5
6Hh35	H	h	35	644	0	6.7

Note: 1 kg/m³ = 1.69 lb/yd³.

Table 4—Expansion measurements

Mixture	Months to expand 0.05%		Months to expand 0.10%		Ultimate expansion	
	20°C	38°C	20°C	38°C	20°C	38°C
5Ho	—	—	—	—	0.04%	0.04%
5Hh25	—	—	—	—	<0.04%	<0.04%
5Hh125	—	—	—	—	<0.04%	<0.04%
5Hh50	—	—	—	—	<0.04%	<0.04%
5Hh150	—	—	—	—	<0.04%	<0.04%
5Hh70	—	—	—	—	<0.04%	<0.04%
5Hh170	—	—	—	—	<0.04%	<0.04%
6Ho	9	2	10	3	0.3%	0.35%
6Hh25	23	5	25	6	0.2%	0.25%
6H125	39	11	—	17	0.05%	0.15%
6Hh50	—	33	—	—	<0.04%	0.07%
6Hh150	—	—	—	—	<0.04%	<0.04%
6Hh70	—	—	—	—	<0.04%	<0.04%
6Hh170	—	—	—	—	<0.04%	<0.04%
7Ho	7	2	14	3	0.35%	0.40%
7Hh25	14	4	20	5	0.30%	0.35%
7Hh125	16	4	20	5	0.25%	0.35%
7Hh50	51	23	—	50	0.08%	0.12%
7Hh150	51	27	106	80	0.10%	0.12%
7Hh70	—	27	—	—	<0.04%	0.05%
7Hh170	—	20	—	50	<0.04%	0.10%
8Ho	8	2	12	3	0.45%	0.40%
8Hh25	15	4	20	5	0.40%	0.40%
8Hh125	18	4	24	7	0.30%	0.40%
8Hh50	57	20	70	23	0.10%	0.10%
8Hh150	—	52	—	—	<0.04%	0.05%
8Hh70	—	—	—	—	<0.04%	<0.04%
8Hh170	—	—	—	—	<0.04%	<0.04%
5Mo	22	5	27	8	0.15%	0.20%
65Mh25	39	10	69	13	0.10%	0.20%
5M125	28	8	57	11	0.15%	0.25%
5Mh50	—	34	—	—	<0.04%	0.07%
5M150	—	15	—	—	<0.04%	0.08%
5Mh70	—	34	—	—	<0.04%	0.05%
5M170	—	23	—	—	<0.04%	0.08%
6Mo	11	3	14	4	0.35%	0.50%
6Mh25	28	10	40	12	0.20%	0.30%
6M125	23	8	27	9	0.30%	0.35%
6Mh50	57	33	—	—	0.05%	0.09%
6M150	—	20	—	35	0.04%	0.10%