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

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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 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 meter (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 C989-05 [3] (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 by 8 ft by 32 ft). The block was cast in a single nominal 58 m^3 (76 yd^3) 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 m^3 (62 yd^3) monolithic casting. The specified concrete properties, all of which were achieved, were 30 MPa (4350 psi) at 28 days compressive strength, 4-8% air content, and 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 m^3 (52 yd^3) 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 form an instrumented mass-concrete element is shown in Figure 1.

ASTM C186[4] work by the authors in 1995 (Fig. 2), using a cal/g maximum limit for heat generated by the 7-day age, suggested that 50-75%, 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 m^3 (9600 yd^3) 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 27.7-31.9 MPa (4010-4630 psi, the range of the results, typ.) to 32.9-38.3 MPa (4770-5550 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 m^3 (16,700 yd^3) 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 m^3 (2000 yd^3) 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.

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 m^3 (600 yd^3) or more. All told, over 5350 m^3 (7000 yd^3) of slag-cement concrete were used in the stilling basin. The concrete mixture featured 222 kg/m^3 (375 lb/yd^3) of slag cement, had a total cementitious materials content of 297 kg/m^3 (500 lb/yd^3), 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 m^3 (640 yd^3) of mass concrete. All told, 5350 m^3 (7000 yd^3) 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 4-10 °C (40-50 °F), initial concrete temperature was 21-24°C (70-73°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-hr 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 (7,000 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.

Bethelehem Steel Caster Foundations—From September, 1995 to January, 1996, over 8400 m^3 (11,000 yd^3) of 65% slag-cement concrete was cast into foundations for a new continuous caster at the Bethelehem 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 m^3 (500 yd^3) 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 m^3 (300 yd^3) 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/m^3 (520 lb/yd^3) 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 m^3 (100 yd^3) 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, Ohio.

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 m^3 (110 yd^3) 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/m^3 (620 lb/yd^3) 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).

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 (half-mile) 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/m^3 (635 lb/yd^3) 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.M 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 a 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 m by 11 m by 4 m (72 by 35 by 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 m^3 (2200 yd^3) 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/m^3 (517 lb/yd^3) 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 m^3 (2300 $yd^{3)}$ of the Grade 100 mass-concrete mixture were cast in a continuous placement in a 12-hr 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 m^3 (8360 y^3) placement over a 23-hour period, which began on the evening of November 7, 2003 and ended on Saturday the 8^{th} (Fig. 8). A nominal 3.3 m (7ft 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 C186[4] 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/m^3 (480 lb/yd^3) coupled with a 0.48 *w/cm*. High-range water-reducing admixture was added at the concrete plant to control the slump to 150-200 mm (6-8 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[5]—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 Grade 80 slag cement was available, so the Corps used it.

Table Rock Lake Auxiliary Gated Spillway[5]—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/m^3 (1080 lb/yd^3) of ASTM C33 No. 67 [nominal 19 mm (3/4 in.)] coarse aggregate, 344 kg/m^3 (580 lb/yd^3) of No. 8 [nominal 10 mm (3/8 in.)] coarse aggregate, and 682 kg/m^3 (1150 lb/yd^3) 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 m^3 (1600 yd^3) 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 m^3 (50,000 yd^3) 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/m^3 (610 lb/yd^3), 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 233. 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 70-80% range is suggested; for Grade 100, the 60-80% 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 mid-west USA at 7 days	ASTM C989 SAI average of last five results; requirement at 28 days	Typical as measured SAI results for mid-west USA at 28 days	Typical Blaine fineness for mid-west 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

Table 2—Typical slag-cement chemistry (a)

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_2O_3	7.1	0.3	7.9	0.6	9.6	1.1
Fe_2O_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	—

Note: *GBFS is glass. As such, there is no CaO, SiO_2, 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		Lab cured	TMC†				
at 3 days	MPa	7.9	19.8	—	—	—	—
at 7 days	MPa	17.4	23.6	—	—	—	—
at 14 days	MPa	25.8	24.5	13.5	26.8	19.7	16.1
at 28 days	MPa	28.3	28.4	34.1	34.3	37.1	31.6
at 56 days	MPa	39.6	35.6	44.3	37.2	48.4	43.6

Note: *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; ‡a water reducer/retarder was used.

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/m³	350	350	320		326	334
	lb/yd³	590	590	539		549	563
CA size*	mm	—	—			25	19
CA size	in.	—	—			1.00	0.75
CA amount at SSD*	kg/m³	—	—	1009		1185	1093
CA amount at SSD	lb/yd³	—	—	1700		1997	1842
FA amount at SSD*	kg/m³	—	—	795		759	781
FA amount at SSD	lb/yd³	—	—	1340		1279	1316
Water at SSD aggregates	kg/m³	—	—			163	177
Water at SSD aggregates	lb/yd³	—	—			275	298
w/cm		0.45	0.48	0.45		0.50	0.53
Slump, spec. max.	mm	—	—	203		—	—
Slump, spec. max.	in.	—	—	8.0		—	—
Slump	mm	—	—			140	—
Slump	in.	—	—			5.5	—
Specified air	%	—	—	6 +/- ½		—	—
Air content	%	—	—			6.0	—
Air temp. at plant		—	—	4-10ºC	40-50ºF	—	—
initial concrete temp.		—	—	21-24ºC	70-73ºF	—	—
Max. concrete temp.		—	—	73ºC	163ºF	—	—

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 4—job data: Wabasha Street Bridge; Rock 'N' Roll Hall of Fame and Museum; Johnstown, PA Air Force Facility (con't)

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				
Max.differential temp.†		—	—	22ºC	39ºF	—	—
f'_c	MPa	27.5	27.5	27.6		27.5	—
f'_c	psi	3990	3990	4000		3990	—
comp. strength							
@ 7 days	MPa	—	—	—		26.2	—
@ 7 days	psi	—	—	—		3800	—
@ 28 days	MPa	32.3 to 35.1	27.7 to 31.9	—		40.0	—
@ 28 days	psi	4680 to 5090	4010 to 4630	—		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, Ohio				Columbiana, Ohio			
Application	Machine base				machine base			
slag cement amount	65%				65%			
total cementitious	297	kg/m³	500	lb/yd³	297	kg/m³	500	lb/yd³
CA size	25	mm	1	in.	25	mm	1	in.
CA amount at SSD	1074	kg/m³	1811	lb/yd³	1009	kg/m³	1700	lb/yd³
FA amount at SSD	875	kg/m³	1475	lb/yd³		kg/m³		lb/yd³
water at SSD aggs.	166	kg/m³	280	lb/yd³	122	kg/m³	205	lb/yd³
w/cm	0.56				0.41			
water-reducing admixture	263	ml/m³	15	fl oz/yd³	263	ml/m³	15	fl oz/yd³
high-range water-reducing admixture	1122	ml/m³	64	fl oz/yd³	1122	ml/m³	64	fl oz/yd³
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/m³	150.6	lb/ft³	2429	kg/m³	151.6	lb/ft³
initial concrete temperature		°C		°F	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 diameter plastic cylinder molds				152.4 mm diameter plastic cylinder molds to 28 days‡			
at 7 days	24.1	MPa	3500	psi	28.3	MPa	4100	psi
at 14 days	—	MPa	—	psi	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: *152.4 mm by 304.8 mm cylinders (6 by 12 in.); †101.6 mm by 203.2 mm cylinders (4 by 8 in.); ‡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/m^3	517	lb/yd^3	333	kg/m^3	560	lb/yd^3
CA size§	19	mm	3/4	in.	~31	mm	~1.25	in.
CA amount @ SSD		kg/m^3			1063	kg/m^3	1790	lb/yd^3
FA amount @ SSD		kg/m^3			775	kg/m^3	1300	lb/yd^3
water @ SSD aggs.					168	kg/m^3	283	lb/yd^3
Water-reducing admixture							Was used	
average slump*	222	mm	8 ¾	in.	178	mm	7	in.
air content*	1.4		%		1		%	
unit weight*	2381	kg/m^3	148.3	pcf	2403	kg/m^3	150.0	lb/ft^3
time of setting (ASTM C 403)								
Initial					6:20		hr:min	
Final					8:40		hr min	
f'_c					34.5	MPa	5000	psi
Compressive strength					Fresh concrete testing**			
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 **4 by 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.

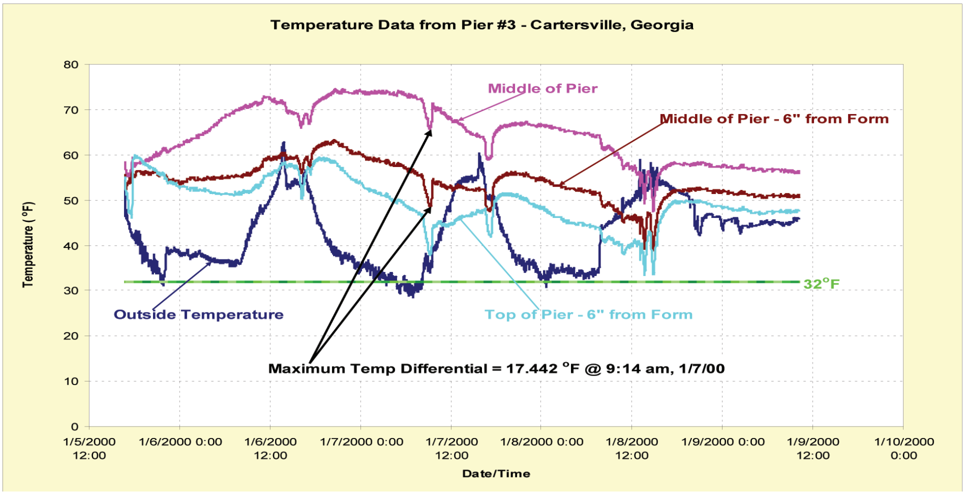
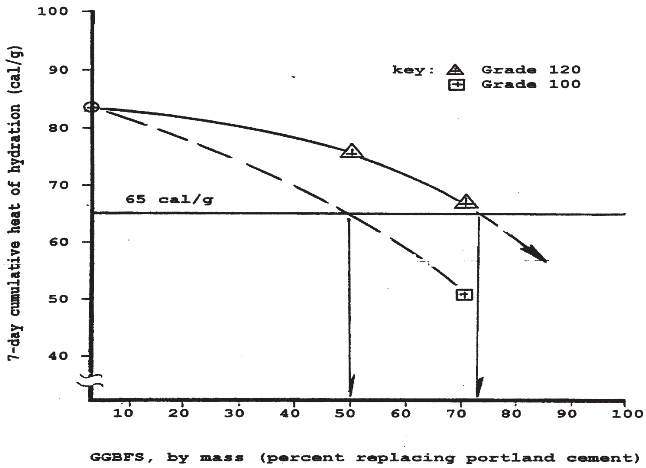


Fig. 1—Holcim (US) Inc. cement terminal expansion project, Cartersville, Georgia; Temperature Chart, as supplied, including units, from project personnel from the third pier casting 1/7th/2000, 65% slag cement (selected dual units: temp. differential of 17.4ºF = 10ºC; 6 in. = 152 mm).



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).

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

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

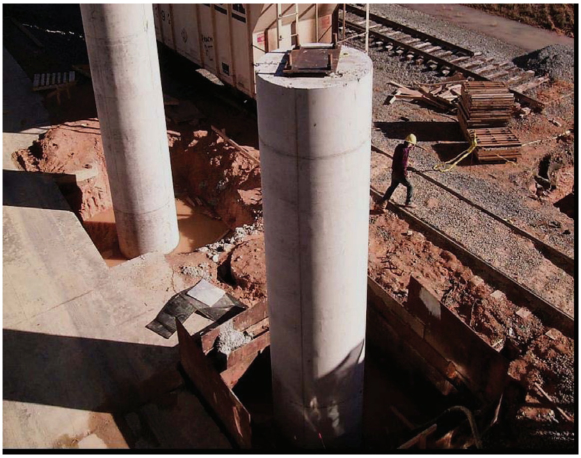


Fig. 5—Holcim (US) Inc. terminal expansion, Cartersville, Georgia;65% slag-cement concrete; winter of 1999-2000.

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

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

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