Bridge Views

Ultra-High Performance Concrete in Iowa

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The center span of this bridge in Buchanan County utilized UHPC.

With funding support from the Federal Highway Administration's (FHWA) Innovative Bridge Research and Deployment (IBRD) program and the Iowa Highway Research Board (IHRB), Iowa has been developing a base of design and construction experience with ultra-high performance concrete (UHPC). With the funding provided, two bridge projects have been completed using the UHPC material. The first was a single-span, 110-ft (33.5-m) long, prestressed I-girder bridge in Wapello County with the girders cast using UHPC. The second was a three-span bridge in Buchanan County with the center span cast with UHPC using the pi-girder cross section developed by the FHWA and the Massachusetts Institute of Technology. In a continuation of this work and with funding from the FHWA Highways for Life program, the Iowa Department of Transportation (Iowa DOT) and Wapello County are working on a third bridge project where a precast deck will use UHPC in a waffle configuration. This article gives an overview of the work that has been done by Iowa with UHPC.

Background

Developed in France during the 1990s, UHPC has seen limited use in North America. UHPC consists of fine sand, cement, silica fume, and quartz flour in a dense, low water-cementitious materials ratio (0.15 to 0.19) mix. Compressive strengths of 18,000 to 30,000 psi (124 to 207 MPa) can be achieved, depending on the mixing and curing process. The material has a low permeability and high durability. To improve ductility, steel or polyvinyl alcohol (PVA) fibers (approximately 2% by volume) are added, replacing the mild steel reinforcement. For these three projects,

the patented mix Ductal® marketed by Lafarge North America was used with steel fibers.

Wapello County Bridge

Iowa was first introduced to UHPC with a bridge project in Wapello County, which was completed in 2006. The UHPC mix was used in the fabrication of four modified Iowa bulb-tee beams. Beam capacity was verified by flexure and shear tests on a 71-ft (21.6-m) long prestressed bulb-tee beam that was tested by the Bridge Engineering Center at Iowa State University. The remaining three 110-ft (33.5-m) long, prestressed concrete bulb-tee beams were then used in a single span, integral abutment bridge replacement project known as the Mars Hill Bridge, south of Ottumwa, Iowa.

Buchanan County Bridge

Buchanan County and the Iowa DOT were given the opportunity to build upon the experience of the first project with a second project in 2008. The project made use of the optimized pi-shape girder that was developed by the FHWA. Five pi-girders were cast at a Lafarge plant in Winnipeg, Manitoba, Canada. Two 25-ft (7.6-m) long beams were tested at the FHWA Turner-Fairbank Highway Research Center and three 51-ft (15.5-m) long beams were used for the center span of Jakway Park Bridge in Buchanan County.

The replacement bridge project that used the pi-girders was located on a county road (136th Street) over the east branch of Buffalo Creek in northeast Buchanan County, Iowa. The bridge is 25 ft (7.6 m) wide by 115 ft 4

in. (35.2 m) long with a center span of 52 ft 0 in. (15.9 m) from center to center of the pier caps. The 50-ft 0-in. (15.2-m) simple span pi-girder is supported on plain neoprene bearing seats with the beam ends encased with cast-in-place concrete diaphragms. End spans are cast-in-place reinforced concrete slabs with integral abutments supported on steel piles. The pier caps are supported on steel piles encased in concrete. The use of the pi-girders provided a complete superstructure system and eliminated the need for an independent deck or wearing surface. Load testing of the pi-girder bridge was conducted by the Bridge Engineering Center at Iowa State University.

Future Work

The work with UHPC is continuing with a third bridge project now under devolvement with Coreslab of Omaha, Wapello County, and the Iowa DOT. This project will use the UHPC mix in a precast deck on a single-span prestressed concrete beam bridge. To optimize the material, the deck panels will be cast using a waffle shape. The current schedule is to cast panels for testing during the fall of 2009. Production panels will then be cast for construction in the summer of 2010.

By using UHPC in bulb-tee beams, the optimized pi-girder, and waffle deck, the project team is expanding the knowledge base and facilitating the wider use of advanced cementitious materials to solve specific problems in the highway transportation system.

More Information

More information about the Iowa projects and UHPC is available in the following documents or contact the lead author at dean.bierwagen@dot.iowa.gov.

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Graybeal, B. A, "Structural Behavior of Ultra-High Performance Concrete Prestressed I-Girders," Federal Highway Administration, Report No. FHWA-HRT-06-115, 2006, 104 pp.

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Wipf, T., Phares, B., Sritharan, S., Degen, B., and Giesmann, M., "Design and Evaluation of a Single-Span Bridge Using Ultra-High Performance Concrete," Final Report to the Iowa Department of Transportation, 2008.

The concrete on the San Francisco-Oakland Bay Bridge made extensive use of fly ash.
Photo: California Department of Transportation

Experiences with Ohio HPC Bridge Decks with Warranty Program

Jim Welter, Ohio Department of Transportation

The environmental benefits aside, greener concrete has been chosen for many of the new east spans of the San Francisco-Oakland Bay Bridge as a practical construction material as well as for durability. In these cases, environmental benefits were not the motivation, but rather the need to meet requirements of design and construction.

There are four distinct construction projects completed or underway, some with multiple contracts, to build the 2.2-mile (3.6-km) long bridge across San Francisco Bay between Oakland and Yerba Buena Island. The new bridge will replace the seismically vulnerable east spans of the 1936 San Francisco-Oakland Bay Bridge.

The new bridge from east to west comprises the Oakland Touchdown, the Skyway, the Self Anchored Suspension (SAS) bridge, and the Yerba Buena Island Transition. The Oakland Touchdown uses low-level, post-tensioned, cast-in-place concrete box girder bridges. The west end of these twin parallel bridges connects to the Skyway. The Skyway, now completed, is a 1.5-mile (2.4-km) long precast segmental structure that used the balanced cantilever construction method. The SAS bridge is the signature structure and connects the Skyway to the Yerba Buena Island shore. The SAS bridge will be a single tower bridge with asymmetrical spans. The Yerba Buena Island Transition structures will be prestressed concrete box girder bridges. They will connect the west end of the SAS to the Yerba Buena Island Tunnel.

Construction began with the Skyway. For durable concrete, California Department of Transportation (Caltrans) has required that 25% of the cementitious material be fly ash in almost all of its structural concrete to mitigate Alkali Silica Reactivity (ASR) since 1997. Thus all the concrete on this massive project required at least 25% fly ash. Higher percentages of fly ash were utilized for the large footings and other mass concrete elements. For the pier concrete, the Contractor, instead of using fly ash, chose to use 50% ground granulated blast-furnace slag, which was the maximum percentage allowed by the 2001 specifications. Bid

prices indicated that this can be an economical benefit to the contractor as there was no requirement or even encouragement for its use. Though by today's rapidly changing standards, the amount of supplementary cementitious materials used was modest in the 450,000 yd³ (344,000 m³) of concrete in the Skyway, the Environmental Protection Agency in 2006 recognized Caltrans as a leader in the construction use of waste products.

The west end of the SAS terminates at a massive pier bent. Here the suspension cables will loop around on saddles and head back toward the east end. The span on the west side nearest San Francisco is shorter then the span east of the tower. This creates an uplift on the west side that is countered by massive concrete anchors as well as the weight of the 8200 yd3 (6300 m3) concrete bent cap. Four columns supporting each end of the bent rest on 63x63x33 ft (19x19x10 m) anchorage blocks. To satisfy the restrictive thermal and corrosion requirements, the concrete contained 674 lb/yd³ (400 kg/m³) of cementitious materials including 40% fly ash. In 2004, this was considered a high percentage for California bridge concrete. Compressive strengths were over 9000 psi (62 MPa) at 90 days.

The portion of the Oakland Touchdown now under construction is 1080 ft (330 m) long and has seven spans over six piers. Under the piers are mass concrete pedestals, which sit on mass concrete pile caps that make up the footing. The pile caps vary in size having a footprint from 46 ft (14 m) square to 52x72 ft (16x22 m). In a cost savings move, Caltrans proposed a passive thermal control plan using 50% fly ash mixes to replace the contractors active thermal control system, which used internal cooling pipes. These mixes had 337 lb/yd³ (200 kg/m³) of fly ash and 337 lb/yd³ (200 kg/m³) of portland cement. The water to cementitious materials ratio was 0.4, the maximum permitted by the specifications for corrosion control. The strength requirement was 5000 psi (35 MPa) at 90 days for the pedestal and 4350 psi (30 MPa) for the pile cap. The average measured strength for all the pedestals was 4620 psi (31.8 MPa) at 28 days and 5720 psi (39.4 MPa) at 56 days. The graph below shows the 28- and 56-day strengths for the pile caps. The average strengths were 4630 psi (31.9 MPa) and 5630 psi (38.8 MPa), respectively. The lowest strengths occurred on samples stored during a 2- to 3-month period when temperature control of the curing room was malfunctioning. A few samples tested at 7 days had average strengths of about 3000 psi (21 MPa). Concrete from four pedestals had an average 90-day strength of 6230 psi (43.0 MPa). One 180-day test result was 6830 psi (47.1 MPa).

As Caltrans strives toward complying with California's Assembly Bill 32 to reduce greenhouse gases, the Bay Bridge project is an example showing that this need not be a tradeoff with efficient concrete mixes.

Further Information

For further information about the mass concrete used in the San Francisco-Oakland Bay Bridge, please contact the author at ric_maggenti@dot.ca.gov.
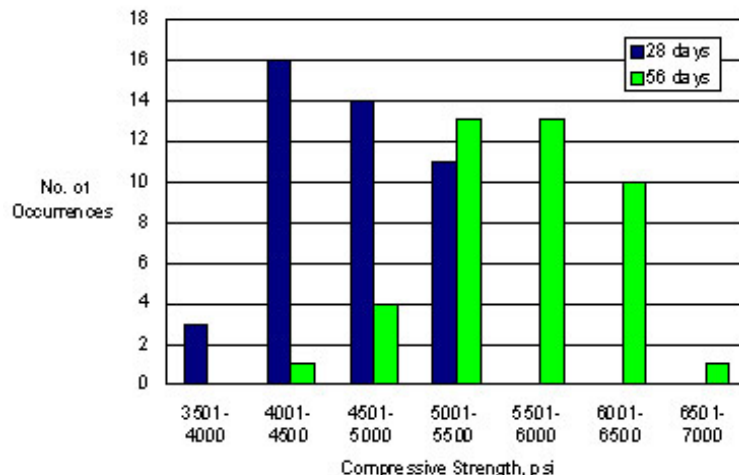
Measured compressive strengths of concrete used in pile caps.

A concrete compressive strength of 10,000 psi (70 MPa) was specified for the precast superstructure and column segments.

High Strength Concrete for the Roslyn Viaduct

Patricia Barnes, Larry McAllen, and Wayne Moore, Bayshore Concrete Products

Long Island, NY, famous for heavy and congested traffic patterns, needed to replace a key bridge over Hempstead Harbor in Roslyn. The original steel superstructure of the Roslyn Viaduct opened in 1949 with two lanes of traffic in each direction. Today, it carries approximately 38,000 cars and trucks each day. This aging bridge had deteriorated and needed to be replaced with a modern, sustainable bridge.

A precast, prestressed, variable depth, concrete segmental structure was the chosen technology for the new viaduct. This is Long Island's first precast concrete segmental bridge. Several factors went into the decision making

process, including a streamlined construction timeline by using pieces that are all cast offsite and the service life of a precast concrete bridge, which is targeted to be 60 to 100 years. Bayshore Concrete Products Corporation (BCP) located in Cape Charles, VA, was contracted to produce all 348 superstructure segments and 64 pier box column segments.

The twin structures of the new bridge will each have nine spans and eight pier columns with each structure carrying the traffic in one direction. The span lengths vary from 121 to 292 ft (36.9 to 89.0 m) and thus, the radius of curvature of the bottom of each

span varies. As a result, each segment is unique. The 64 pier columns segments have a ship-lap architectural profile achieved by using formliners.

BCP faced multiple challenges with this project. Production of the segments was accomplished with the use of four casting machines. Two casting machines produced the girder segments with depths ranging from 10 to 4 ft (3.05 to 1.21 m). Another casting machine produced the girder segments with depths ranging from 17 to 10 ft (5.18 to 3.05 m), and the fourth casting machine was used for all pier segments. The shallower girder segments were the most abundant and

the most critical to the schedule, hence the reason for two casting machines.

No two adjacent segments were exactly the same size or shape. Except for the starter segment, all segments were match cast against each other. The varying depth of the segments required formwork modifications every time. Within the form crew, smaller crews prepared the form sections in advance. Each casting machine had three soffit tables to allow advance setup. The erector's anticipated schedule was aggressive so the time for formwork changes between castings had to be kept short.

Geometry control was another challenge. Geometry control was achieved by using the short-line match casting method. A typical casting run would start with the starter segment and end at the first wet joint. Each span generally consists of 20 to 23 segments with wet joints at midspan and at five or six segments away from midspan. The first cantilever girder segments were match-cast to each side of the girder pier segment. This required the double handling of 85 to 95 ton (77 to 86 Mg) girder pier segments; once to cast the upstation cantilever and a second time to cast the downstation cantilever.

In addition, this project required the consistent production of quality segments with sensitivity to the aesthetics of the precast units. The project required that BCP develop a concrete mix design that had the flow and consolidation characteristics of self-consolidating concrete as well as stringent high performance concrete requirements. The project specifications required that the concrete achieve a strength of 10,000 psi (70 MPa) at 56 days for both superstructure and columns. This strength was typically achieved in 14 days using the concrete mix proportions shown in Table 1.

In addition to the typical field tests such as spread or slump, entrained air content, and temperature, each delivered load of concrete was tested for compliance to water content in accordance with AASHTO TP 23 (now T 318) Water Content of Freshly Mixed Concrete using Microwave Oven Drying. A water-cementitious materials ratio between 0.29 and 0.33 was required for an acceptable batch. To achieve these concrete qualities, it was necessary to incorporate a high-range water-reducing admixture, a water reducer-retarder, and a corrosion inhibitor.

The contract specifications also required that the concrete meet specific values for freeze-thaw durability, scaling resistance, chloride permeability, air content, modulus of elasticity, creep, and shrinkage. The specified values and actual results are shown in Table 2.

Over 4.5 million lb (2 million kg) of reinforcement was required for this project with uncoated bars used for all reinforcement enclosed in the segment concrete and stainless steel bars used for the projecting reinforcement. The reinforcement was very congested making placement difficult and typical segments very heavy. Some segments had so much reinforcement that no light was visible through the casting cell.

Segments were cured using steam. Except during the winter, very little steam was needed since the concrete mix generated most of its own heat. The application of steam was mostly to maintain a moist environment within the curing enclosure. The shear size of some of the segments

Table 1

Material	Quantities (per yd³)	Quantities (per m³)
Cement, Type III	760 lb	451 kg
Silica Fume	57 lb	34 kg
Fine Aggregate	1313 lb	779 kg
Course Aggregate[1]	1565 lb	929 kg
Water	270 lb	160 kg
High-Range Water-Reducing Admixture	100 fl oz	3.87 L
Water-Reducing/Retarding Mixture	49 fl oz	1.90 L
Corrosion Inhibitor	5.4 gal	26.7 L
Air Entraining Admixture	12 fl oz	.46 L
Water-Cementitious Materials Ratio	0.33	0.33

made curing a challenge. Thermocouples in the enclosure and embedded in the concrete were used to monitor temperatures during curing to ensure that enclosure temperature was uniform over the entire piece.

Finally, each segment, superstructure, and column had to be hand rubbed for a smooth finish and a silane coating had to be applied, then approved and accepted by the NYSDOT inspector. Tully Construction, the project contractor, also had a representative at BCP to inspect each segment. All of the pieces were barged close to the job site and then transported by road using special trailers.

Further Information

For further information about the segment production, please contact the first author at patricia.barnes@skanska.com.

Table 2

Property	Test Method	Specified	Measured
Compressive Strength at 56 days	AASHTO T 22	≥ 70 MPa	82.0 MPa
Freeze/Thaw Durability after 300 cycles	AASHTO T 161 Procedure A	≥ 80%	95%
Scaling Resistance	ASTM C672	≤ 3	1
Chloride Penetration	AASHTO T 259 Modified	≤ 0.025% at 25 mm	0.013% at 35 mm
Air Content	AASHTO T 152	> 5%	6.0%
Modulus of Elasticity	ASTM C469	≥ 30 GPa	36.8 GPa
Creep after 56 days of loading	ASTM C512 1 Test at 49 MPa 1 Test at 70 MPa	≤ 60 mill./MPa	35.05 mill./MPa 21.75 mill./MPa
Shrinkage after 56 days of drying	AASHTO T 160-97 (at 70 MPa)	< 600 mill.	70 mill.
Water-Cementitious Materials Ratio	AASHTO TP 23-93	< 0.40	0.29

Importance of End Surface Preparation when Testing High Strength Concrete Cylinders

Mathew Royce, New York State Department of Transportation

With increasing compressive strength, the modulus of elasticity or the slope of the elastic stress-strain relationship increases, and the magnitude of inelastic post-peak strain capacity decreases. Stated differently, as strength increases, concrete becomes increasingly brittle and more sensitive to testing-related variables. Some of the most influential variables include specimen geometry and size, age, moisture content, moisture distribution, end preparation, loading rate, and testing machine parameters. In this article, end preparation will be discussed.

Bonded Caps or Ground Ends

When testing high strength concrete, end preparation is one of the most important variables influencing the compressive strength results. Tolerances for perpendicularity and end planeness are provided in AASHTO T 22. Carino et al.[1] investigated the significance of sulfur capping and grinding using concrete with strength levels of 6500 psi (45 MPa) and 13,000 psi (90 MPa). No strength difference due to the method of end preparation was observed for the lower strength concrete, but for the higher strength concrete, grinding re-sulted in as much as 6% greater measured strength.

Capping Material Thickness

The appropriateness of capping compounds depends to a large extent on the cap thickness provided. Lessard et al.[2] found a commercially available "high strength" capping compound to be satisfactory when used for testing concrete with strengths up to approximately 17,000 psi (120 MPa), provided the capping layer is less than 0.12 in. (3 mm) thick. For concrete compressive strengths greater than 7000 psi (50 MPa), AASHTO T 231 (ASTM C617) specifies a maximum aver

Grinding a high strength concrete cylinder.

age cap thickness of 0.125 in. (3 mm) and a maximum thickness for any part of the cap of 0.20 in. (5 mm).

Capping Material Strength

Certain capping materials appear to be suitable for testing high strength concrete; however, the compressive strength of the capping compound alone should not form the sole basis of selection. According to AASHTO T 231, sulfur mortar used with concrete compressive strengths greater than 7000 psi (50 MPa) must be prequalified by the manufacturer for testing at the higher strength levels. In a study by Burg et al.,[3] the performance of a conventional strength capping compound and a "high strength" capping compound were evaluated with respect to their suitability for use in testing high strength concrete. Both capping compounds were sulfur-based and commercially available. As anticipated, the compressive strength of the high strength capping compound

was significantly higher than the conventional capping compound; however, the modulus of elasticity was lower and Poisson's ratio higher for the high strength capping compound. High strength concrete tested with caps made with high strength capping compound had measured compressive strengths lower than the same concretes tested with caps made with the conventional strength capping compound. For the three nominal concrete strengths of 9000, 14,000 and 18,000 psi (62, 97, and 124 MPa), the differences in measured concrete compressive strength were statistically significant and suggested that compressive strength of capping compound is not a reliable indicator for suitability for use in testing high strength concrete. The most suitable means of judging the adequacy of a particular capping compound when testing high strength concrete is by performing comparative testing with cylinders having surface ground ends.

Bonded Caps or Unbonded Caps

Pistilli and Willems[4] compared traditional sulfur caps with unbonded neoprene pads in compressive strength testing of concrete with strengths ranging from 3000 to 18,000 psi (20 to 125 MPa) and compared sulfur caps with specimens having ground and lapped surfaces within the range of 13,000 to 20,000 psi (90 to 138 MPa). Significantly lower within-test variability occurred with neoprene pads compared to the sulfur caps for strengths above 8000 psi (55 MPa). The ratio of 4 x 8 in. to 6 x 12-in. (100 x 200 mm to 150 x 300 mm) cylinder strengths ranged from 0.96 to 1.06. The strength differences due to cylinder size did not appear to be of practical significance for concretes with actual measured strengths ranging from 4000 to 9000 psi (28 to 62 MPa). Grinding the ends of cylinders with measured strengths ranging from 12,000 to 20,000 psi (83 to 138 MPa) showed promise as an improved test procedure for end preparation. Provided the finished surfaces are smooth, neoprene pads could be a satisfactory alternative for concretes with strengths within the range of 13,000 to 20,000 psi (90 to 138 MPa). Currently, ASTM C1231 does not permit the use of unbonded caps for acceptance testing of concrete with a compressive strength above 12,000 psi (80 MPa). For higher strength concrete, the alternative is to grind the ends plane or cap with a suitable sulfur-based capping compound. Also, AASHTO T 231 and ASTM C1231 require qualification tests of bonded and unbonded capping systems, re-

spectively, for use with concrete compressive strengths greater than 7000 psi (50 MPa).

Summary of Existing Standards

For concrete compressive strengths less than 7000 psi (50 MPa), bonded caps, unbonded caps, or ground ends may be used.

For concrete compressive strengths from 7000 to 12,000 psi (50 to 80 MPa), bonded caps, unbonded caps, or ground ends may be used provided that the bonded capping material and unbonded caps have been qualified per the appropriate standards. For concrete compressive strengths above 12,000 psi (80 MPa), bonded caps or ground ends may be used provided that the bonded capping material has been qualified per the appropri-

ate standard.

In all cases, testing of high strength concrete must be performed in strict compliance with the appropriate AASHTO or ASTM procedures.

References

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Further Information

For further information about testing high strength concrete cylinders, please contact the first author at mcaldarone@ctlgroup.com.

Portions of this article are excerpted from "High-Strength Concrete" by Michael A Calderone, published by Taylor & Francis, 2009.

Letter to the Editor from the Silica Fume Association

The following letter was received from the Silica Fume Association concerning the article titled "High Performance Concrete in Colorado," which was published in HPC Bridge Views, Issue 55, May/June 2009.

Editor

The article titled "High Performance Concrete in Colorado" contains a misleading statement regarding the safety of using silica fume in high performance concrete.

A common misconception in the construction industry is that if the labeling of any material contains the word "silica," it must be a health hazard. Silicas (the common name for silicon dioxides) are all around us, both in natural forms and made-made forms. In

fact, silicon ranks second to oxygen in abundance in the earth's crust in the form of silicate minerals and is present as the oxide (silica) in soils and sediments, in some organisms such as diatoms, and in some plants. Silicas are safe for use in construction and other industries following the specific instructions found in that particular product's Material Safety Data Sheet (MSDS). The Silica Fume Association has a mandate to educate and, through the following information, is attempting to correct a common misunderstanding.

Silica fume is recognized by standards organizations and industry specification committees such as the Occupational Safety and Health Administration

(OSHA), the American College of Governmental Industrial Hygienists (ACGIH), the National Institute for Occupational Safety and Health (NIOSH), and ASTM International as a form of amorphous silica. As an amorphous silica, silica fume does not present the same health risks to concrete workers, as do respirable crystalline silicas.

Amorphous silicas share little in common with crystalline silicas. Unlike crystalline silicas, which have long been recognized as a cause of occupational disease, amorphous silicas are not associated with any permanent or debilitating lung or other disorders.

For more than 30 years, silica exposure levels and their health effects have been intensively

studied. As a result, crystalline silicas have become heavily regulated by OSHA, ACGIH, NIOSH, and many other organizations. In 2006, the ACGIH withdrew the threshold limit values (TLV) of respirable silica, (Amorphous – silica fume, Chemical Abstracts Service Registry Number 69012-64-2); thereby supporting the industry practice of following the prescribed cautions in the MSDS for silica fume and treating silica fume as a "nuisance dust" in relation to worker safety.

Silica fume, widely recognized as a valuable ingredient in the production of high performance concrete, makes good sense for producing sustainable concrete structures. Silica fume concrete greatly enhances the service life of many types of structures, especially concrete bridges. We doubt the authors of "High Performance Concrete in Colorado" meant to single out silica fume; rather they may have been highlighting the challenges of using any dusty product in a small bag rather than in bulk silos. We must point out that silica fume is available throughout the United States in bulk form, just like cement and fly ash, and that bulk silica fume is the most common form used in concrete plants. When bulk silica fume is used, the amount of dust created during the batching process is virtually eliminated and workers' exposure to dust at the plant is significantly reduced.

In closing, great care should be taken when evaluating the health risk of any products used in the construction industry. Close attention must be paid to products labeled "silica" as to their specific form being either crystalline or amorphous and the amount of dust generated when dispensing the product.

Executive Board of the Silica Fume Association

Authors' Response

The authors would like to thank the Silica Fume Association (SFA) for their clarification of some of the issues surrounding silica fume. As they have pointed out, using bulk silica fume properly can reduce dust exposure as opposed to the small bag process. Our article was intended to highlight the current state of practice in Colorado only, not disparage any material or material supplier. Silica fume has been and will continue to be a vital component of high performance concrete. We've met with the Director of SFA and look forward to continue working with SFA as well as other material and concrete associations in reaching our goals for high performance concretes.

Andrew Pott and Jamal Elkaissi