HPC Bridge Views

High Performance Concrete Academia States Industry FHWA HPC

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The Colorado River Bridge at Hoover Dam—Overview

Dave Zanetell, Federal Highway Administration

Concrete with a specified compressive strength of 10,000 psi (69 MPa) was used in the arch.
Photo: Central Federal Lands Highway Division, Federal Highway Administration

High performance concrete (HPC) is at the core of the successful construction of the Hoover Dam Bypass. The nearly 5-mile (8-km) long project includes eight separate and significant bridges including the centerpiece Colorado River Bridge at Hoover Dam and officially designated the Mike O'Callaghan-Pat Tillman Memorial Bridge. This monumental 1905-ft (581-m) long structure includes twin rib arches that are the longest in the western hemisphere. The arches span 1060 ft (323 m) and rise nearly 900 ft (274 m) above the Colorado River. The comprehensive $240 million bypass project will open to the public in November 2010 without dispute or claim and within the original budget.

Project Organization and Structure

The Central Federal Lands Highway Division (CFLHD) of the Federal Highway Administration serves as the project manager and leader of the multi-agency and consultant teams. The multi-agency team includes representatives from the Arizona and Nevada Departments of Transportation, National Park Service, Bureau of Reclamation, and the Western Area Power Administration. The CFLHD is responsible for the cradle-to-grave management of all the design, consultant, contracting, and construction activities. The overall project includes six contracts for roadway and bridge structures, including the Colorado River Bridge at Hoover Dam. HDR, Inc. serves as the managing lead of the collective consultant team with T.Y. Lin International as the engineer of record for the Colorado River Bridge. A joint venture of Obayashi Corporation and PSM Construction USA is the prime contractor for the bridge.

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Cradle-to-Grave Approach to Management of Risks and Defining Issues

The incorporation of HPC for the bridge required application of the CFLHD's construction project management approach. Through a two-step process, the team worked together to further assess the feasibility of using HPC. Special attention was given to specification development, feasibility of the final design requirements, and staged pre-bid field reconnaissance to increase competition and reduce bid-day contingencies.

The strategy was to complete many of the significant time-consuming activities such as material source identification and mix viability assessments before bidding because it would have been impractical to complete these during the bidding period. This pre-bid investigative effort, combined with active sharing of information and industry outreach, served to level any competitive advantage and increase competition. It was important to demonstrate that HPC could be batched, cooled, delivered, and placed successfully on this unique project in extreme conditions. This effort also served to validate the design parameters.

The strategy for using concrete involved a series of planned activities that linked design optimization and final requirements with industry capability and the risk associated with specific project requirements. This approach served to integrate requirements, which are typically considered separately, throughout the development, procurement, and construction processes. This strategy further enabled cost-savings through optimization of the design, increased industry competition, and reduced project risks and uncertainties. The overall result was a saving of millions of dollars.

The two-step concrete feasibility and specification development program was planned to ensure quality construction within budget constraints. These were considered to be complementary rather than opposing requirements. To achieve this, a cradle-to-grave approach that integrated all design, technical, contracting, and construction aspects related to the concrete was needed.

Strategic Approach to Concrete Construction

From inception, material selection and application was identified either as a major risk or as an opportunity. The CFLHD and consultant team developed a progressive concrete implementation and risk management strategy. In the first phase, the CFLHD's laboratory staff, in conjunction with the consultant design team, completed a basic study to validate the design parameters and link the final contract requirements with local capabilities. The first report concluded that multiple local sources of aggregates suitable for incorporation into HPC were available. Statistical analysis of previously produced low strength concrete mixes and structural concrete mixes confirmed that mass production of HPC from local sources and suppliers would be possible.

The second phase included an intensive HPC testing program using local materials, performance based specifications, and concrete trial batches. This testing provided a broad range of information that otherwise would not have been available to the bidders. The intent of this phase was to verify the basic feasibility of achieving the required 10,000 psi (69 MPa) concrete compressive strength in a production setting. This phase also provided information about concrete mix designs that might yield the necessary fresh concrete properties for delivery, placement, and consolidation, while providing other information on hardened concrete properties.

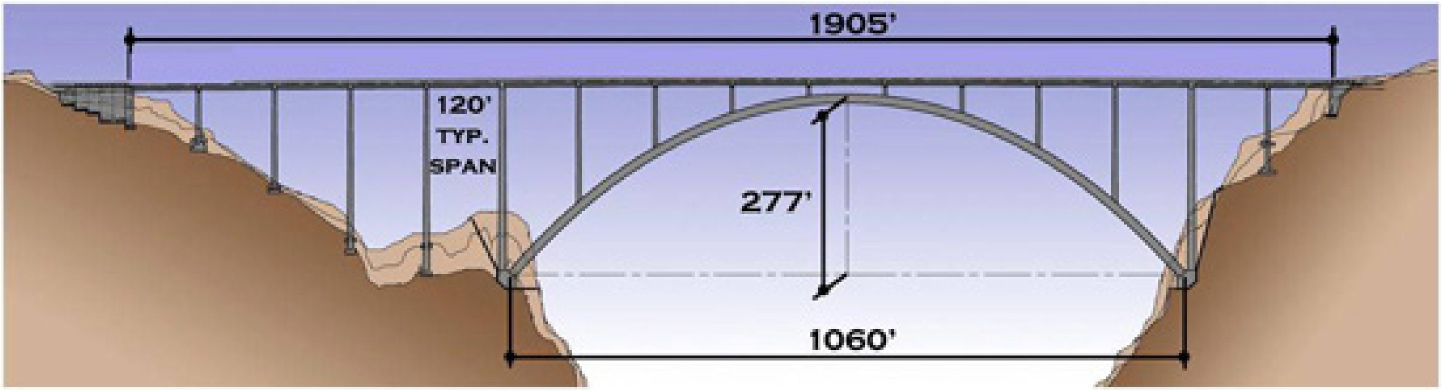
The team took this information and shared it with the industry well in advance of the bid period. The purpose was to seek input and feedback and to raise industry awareness of the project and build pre-bid energy. While this effort did not define a project-specific source of materials or mandatory mix designs, it made the development, production, and placement of the required concrete a non issue during the bidding period. The complete phase one and phase two reports were provided as informational material in the bidder packages.

Summary

This progressive approach adopted for the Colorado River Bridge at Hoover Dam removed all doubt as to availability and viability of successfully meeting the project's requirements for the concrete. It further validated the design team's optimization, while raising industry awareness well in advance of execution. Otherwise, stakeholder and project team confidence entering bid day and beyond would have been limited. A true collaboration between owners, consultants, suppliers, and contractors was achieved.

Further Information

Further information about the project, including construction photographs, are available at www.hooverdambypass.org.



Dimensions of the Colorado River Bridge at Hoover Dam.

The Colorado River Bridge at Hoover Dam—Design Aspects with HPC

David Goodyear, T.Y. Lin International

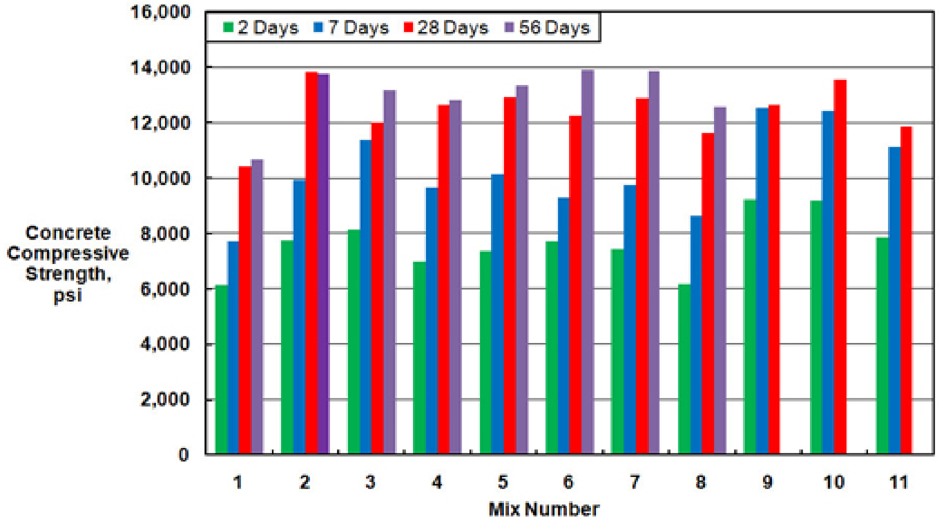
The Colorado River Bridge at Hoover Dam crosses the nearly 900-ft (274-m) deep Black Canyon, and sits downstream of the famous Hoover Dam—a monument to engineering in general and concrete technology in particular. Selection of the right structural system for this bridge meant defining the character of a long-span bridge that respected the pioneering work of the great dam builders, and the grandeur of the Black Canyon setting. Concrete was not the only choice, but certainly the most natural in this setting.

Bridge Type

The bridge type selection was guided through two focus groups. The technical issues were presented to a Structural Management Group (SMG) comprised of the state and federal bridge engineers and peer review consultants. The aesthetic issues were presented to a Design Advisory Panel (DAP) comprised of state historic preservation officers, the National Park Service (NPS), Bureau of Reclamation (BOR), Native American representatives, and architectural consultants. Both the SMG and the DAP groups converged quickly on a deck arch as the correct solution to meet both the engineering and aesthetic demands for the project. Once the options for the arches were presented to the executives of the five leading agencies (the Federal Highway Administration Central Federal Lands Highway Division, states of Arizona and Nevada Departments of Transportation, BOR, and NPS), the unanimous selection of a concrete arch set the direction for design.

High Performance Concrete

High performance concrete (HPC) was the designer's focus from the beginning. There are many characteristics of HPC that provide advantages for a long-span arch, including superior durability, strength, and stiffness. The arch form is an ideal application for concrete owing to the primary compressive strength of a simple concrete box section typically used for the arch rib. In the case of the Colorado River Bridge at Hoover Dam, the 1060-ft (323-m) long arch span required more than just strength. Several aspects of design were controlled by both immediate and time-dependent arch deflections. Here, the stiffness of HPC became an important parameter, surpassing strength in its benefit to design.



Measured concrete compressive strengths from trial mixes.

The customary concrete strengths for highway design in the region of Hoover Dam are on the order of 4000 to 5000 psi (28 to 34 MPa). The preliminary arch designs showed the great advantages of HPC for such a long-span arch, with even ultra-high performance concrete being reviewed for possible application. As the proposal for high strength HPC was advanced, questions were raised about the ability to produce consistent, high strength concrete and deliver it over the canyon. Additionally, the typical questions about material properties, creep, and shrinkage were highlighted due to the 1060-ft (323-m) long span of the arch. As a result, the project design team retained CTLGroup to develop a demonstration program for HPC using the local materials that would be available to the contractor. This allowed comprehensive testing for the key properties of strength, durability, workability, creep, and shrinkage to better inform the design team, as well as give the prospective bidders a reference point for their own mix design work under the construction contract.

Mix Design Program

The mix design program included a range of approaches, virtually all of which confirmed that the 56-day strength target of 10,000 psi (69 MPa) was achievable. Testing results were consistent with published test results and showed the superior properties of HPC in terms of durability and dimensional stability. The low permeability and low specific creep typical of high strength HPC were confirmed. The testing program also supported the project's preference to not require job-specific creep testing in the course of construction. Creep tests are time consuming and, in the opinion of the designer, not well suited for the construction phase of a project that starts off with concrete production. The specific creep measured in the testing program was less than half of that typical for conventional concretes. And while the design proceeded on the basis of conventional creep factors, the dimensional stability of HPC was seen as an additional margin warranted for such a significant structure.

Arch Design

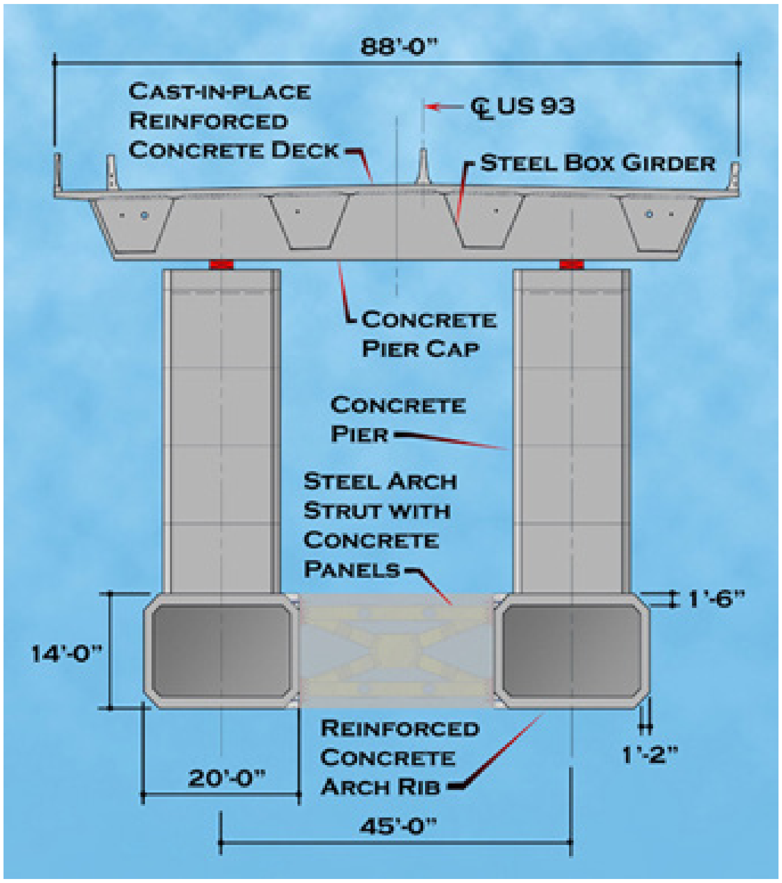
The topography of the site required a high rise to the arch. The high rise of the arch ribs, the use of composite deck construction, and the logistics of form traveler construction led to the use of an open spandrel crown as opposed to an integral crown. This meant that arch stability for asymmetric live load would not rely on integral deck framing at the crown. This same geometry affected the earthquake response of the arch ribs, allowing the more flexible framing system with greater deformation along the bridge, and increasing the period of response to limit seismic demands. The latter are most significant at the arch springing, where traditional arch rib design would include increasing the section size to resist higher moments. HPC allowed for a smaller arch cross section and mass, while maintaining requisite strength and stiffness. Arch deflections also controlled spandrel column design and articulation. Secondary moments in the spandrel columns due to long-term arch deflection were a considerable portion of total demand. The superior stiffness of the HPC was key to using the same prismatic section down to the springing and the integral framing of the end spandrel columns.

Summary

It is difficult to imagine a more appropriate application of HPC than a long-span arch such as the new Colorado River Bridge at Hoover Dam. HPC helped make this magnificent span in the shadow of Hoover Dam possible and practical. And the delivery of consistently high quality HPC by the construction contractor showed that even in the harshest of climates, HPC is an excellent choice for long-span bridge construction.

Further Information

Further information about the design of the bridge is provided in ASPIRE™ Spring 2010.



Typical Section

The Colorado River Bridge at Hoover Dam—Concrete Production and Placement

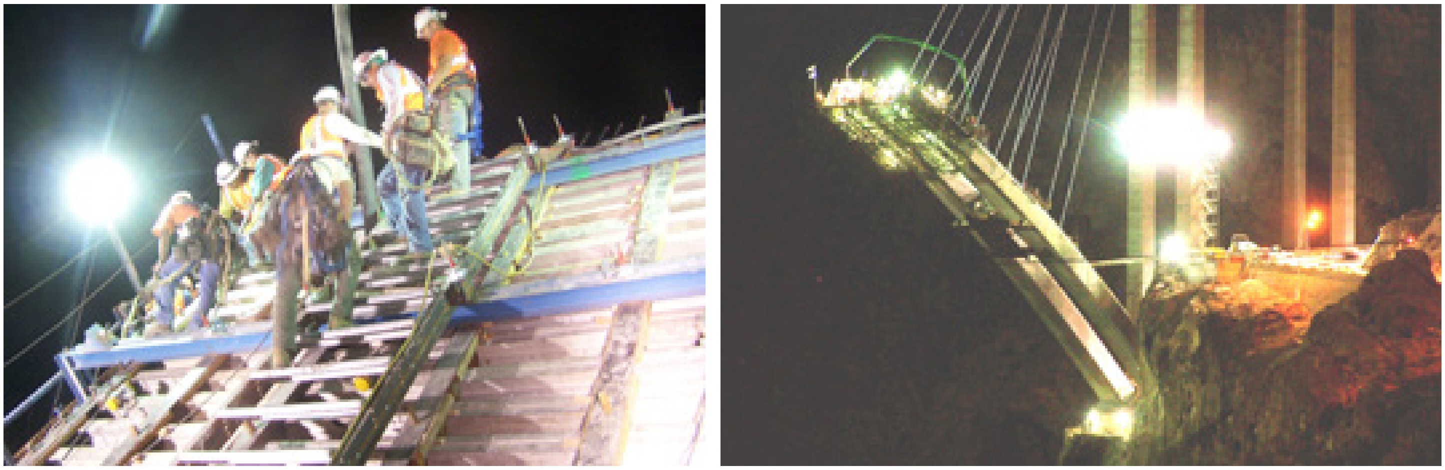
Jeff St. John, Obayashi/PSM Joint Venture

In early-to-mid 2005, the joint venture of Obayashi Corporation and PSM Construction USA began assembling on the project site of the Colorado River Bridge. One of the chief topics of discussion amongst the team was the example of public works adjacent to the site—the Hoover Dam, one of the twentieth century's greatest engineering and construction feats. Discussions hit on many of the usual topics regarding that structure; how did they handle the intense heat of a site, which can approach 130°F (54°C), and how did they get the workers, equipment, and materials to the work site? The same challenges would need to be faced 70 years later.

It was readily apparent that a single challenge dwarfed all others; how to build the concrete arches. The main concern was the concrete itself. This was a multi-faceted concern that involved the mix design, thermal control, concrete delivery and placement, consolidation, and possibly the chief concern of all, quality control.

Work started on developing a mix design 2 years prior to casting the first arch segment. Many of the requirements had been established by the Federal Highway Administration and the designer (T.Y. Lin International). Among these parameters were the required concrete compressive strength of 10,000 psi (69 MPa) at 56 days, aggregate selection to ensure long-term durability, and thermal control requirements to minimize cracking and, again, ensure long-term durability. To these design requirements, the construction team added several others to overcome delivery and placement challenges (pumpability, flowability, and long set time) and schedule challenges (rapid strength gain to minimize the form traveler cycle time). These included compressive strengths of 4000 psi (28 MPa) for launching the form travelers and 6000 psi (41 MPa) for stressing the temporary stays used to support the arch during construction.

The first step was to call in the cavalry: in this case international



Concrete placements for the arch were made at night.

experts. Dr. Ryuichi Chikamatsu from the Obayashi's Technical Research Institute in Japan was brought on-board to primarily consult on the mix design. Paul Jordan of Sika Corporation (the admixture supplier) lent his advice and helped with innumerable trial batches. Dr. Wilbert Langley from Halifax, Nova Scotia, Canada, also consulted on the mix design as well as the thermal control requirements. The mix design used was a direct development of Dr. Chikamatsu and Sika, and the thermal control plan was by Dr. Langley.

Mix Design

The mix design met all of the criteria set for it. Short-term and long-term strengths were achieved using the concrete mix proportions shown in the table below.

This mix typically achieved strengths of 4000 psi (28 MPa) in just over a day and over 12,000 psi (83 MPa) in 56 days. Pumpability and flowability were addressed by the use of a high-range water-reducing admixture, which resulted in concrete slump ranges that neared those of self-consolidating concrete. Set times in excess of 2-1/2 hours were achieved using a retarder.

However, the high cement content had a less desirable effect. The concrete in its natural curing condition would reach temperatures in excess of 190°F (88°C). This was far above the 155°F (68°C) limit of the contract specifications. Most typical mitigation methods, such as using chilled batch water or ice chips, shading the aggregate stockpiles, and casting at night, couldn't come close to reducing the maximum curing temperature to the target range. Only two realistic options remained; circulation of cold water through pipes embedded in the concrete or the use of liquid nitrogen to precool the concrete to a temperature such that its maximum peak curing temperature would be less than 155°F (68°C). Many miles of cooling tubes had been used to control curing temperatures during construction of the Hoover Dam. The location, cycle time, installation, and maintenance issues involved with cooling tubes ruled them out for the bridge. Only the liquid nitrogen option remained.

Material	Quantities (per yd^3)	Quantities (per m^3)
Cement, Type IV	800 lb	475 kg
Fly Ash, Class F	200 lb	119 kg
Fine Aggregate	1252 lb	743 kg
Coarse Aggregate	1515 lb	899 kg
Water	310 lb	184 kg
High-Range Water-Reducing Admixture	50 fl oz maximum	1.93 L maximum
Mid-Range Water-Reducing & Retarding Admixture	20 fl oz maximum	775 mL maximum
Water-Cementitious Materials Ration	0.31	0.31

Liquid Nitrogen

The use of liquid nitrogen allowed the temperature of the concrete during the summer to be lowered from a batched temperature of 85°F (29°C) to a

Letter to the Editor

The following letter was received concerning the article titled "Measurement of Air Content in Concrete," which was published in HPC Bridge Views, Issue No. 61, May/June 2010.

predelivery temperature of 40°F (4°C). In turn, this kept the temperature at point of placement in the 60°F (16°C) range resulting in peak curing temperatures of less than 150°F (66°C). The cost of using liquid nitrogen to cool concrete is very high. During the heat of a southern Nevada summer, the cost of the nitrogen required for cooling often exceeds \$100/yd3 (\$131/m3). However, the high cost was mitigated by the minimal effort needed in other activities. No maintenance for water supply and form insulation and no mitigation efforts such as grouting of cooling tubes and leaving forms in place for an extended duration were required. The precooling resulted in a product that did not require any further thermal control measures and, with the unique bridge structure and location, offered the only viable option.

The nitrogen-cooled concrete was beneficial to the placement system during the very warm summer months, where even temperatures at night occasionally did not fall below 100°F (38°C). During the very hottest portions of the summer, it was necessary to precool the concrete pumping line by filling it with chilled water prior to the placement, wrapping it with burlap, and soaking the burlap with chilled water to reduce heat gain through the placement system.

Concrete Delivery

Planning for concrete delivery and the placement system preoccupied the team for a long time. Two options were apparent to get the concrete to the point of placement; use of a pumping system or delivery by cableway (high-line) concrete bucket. Delivery by bucket to the point of placement (the same methodology used for construction of the Hoover Dam) was discarded for several reasons, not the least of which were tying up a critical resource for several hours nearly every day and the size of buckets required to maintain precise control of discharge into a very small target area of the placement openings in the traveler cover forms. The decision was made to use a concrete pumping system.

Challenges for pumping included the harsh aggregates of the concrete mix, the long pump line, the means to place through the restricted openings, and delivery of concrete to the pump. Trailer pumps, specially modified to handle the harsh local aggregates, were selected due to their ability to fit in the tight areas available for setup. Delivery to the pump was easy on the Nevada side of the gorge. The pump could be set up on the roadside that is very near the arches and concrete delivered by truck. The Arizona side, with its tremendously steep cliffs, was another story. There, the trailer pump was set up on the base of the arch in conjunction with a 5 yd3 (3.8 m3) re-mixer. Concrete was discharged from the delivery truck into 8 yd3 (6 m3) concrete buckets supported by the cableway and lowered to the re-mixer, where the buckets were discharged. Use of the re-mixer allowed the buckets to be re-hoisted nearly immediately to receive the next load of concrete. Tying up the cableways for these placements was a significant issue but no other realistic option was identified.

From the trailer pump, the concrete was pumped up the arch through a 5-in. (125-mm) diameter heavy wall line over a distance of 600 ft (183 m) horizontally and 250 ft (76 m) vertically to a 105-ft (32-m) long placing boom mounted on the arch near the form traveler. This placing boom allowed precise control of discharge. A typical arch segment placement took 4 to 5 hours.

Concrete Consolidation

Consolidation of the concrete in the formwork was a major concern. The geometry of the arch, with many segments placed at a steep angle, required the use of top surface forms. Openings were established in the forms, not only for placement, but also to allow the use of high-cycle concrete vibrators. In addition, external vibrators were mounted under the bottom soffit form and along the side forms to help eliminate any issues due to the lack of concrete consolidation. As a tribute to the hard-working concrete placement crew, very little honeycombing was encountered when the forms were removed.

Quality Control

During the planning sessions, an

often discussed topic was quality control. One bad load of concrete could plug up the placement system and lead to a half-completed segment, which would need to be removed. Another concern, a load of low quality concrete could fail to achieve strength, which might not be determined until several segments later. The financial implications and loss of schedule and momentum would be staggering. It was obvious that the quality control efforts needed to go above and beyond the usual industry standard.

Experience from the footing construction demonstrated that traditional ready-mix concrete batching would not meet the quality requirements of the arch concrete. Too many aspects of the concrete are subject to variations such as the batching efficiency of the truck's mixing drum and the drive time. After much discussion and research, a portable batch plant incorporating a 5 yd³ (3.8 m³) pan mixer was purchased and set up on the project site.

Pan mixers use high speed paddles to premix the concrete prior to discharging into the truck. They are most traditionally used in precasting plants but were perfect for the application since quality, not volume per hour, was the most important issue. The batch plant operator was a master at determining the quality of the predischarged concrete and was able to make adjustments such that the slump of the concrete rarely varied more than 1/2 in. (13 mm) during a placement. The Quality Control Manager personally tested every single load of concrete prior to sending it to the pump. The proximity of the plant to the site made it extremely easy to make adjustments throughout the course of any placement.

The success of all of these efforts can be seen in the finished bridge. No delays were encountered during arch construction due to pumping or placement issues, nor were any problems encountered with the quality of the concrete. The arch construction actually went faster than anticipated and resulted in a monument that nearly rivals the beauty and awe of its neighbor.

Further Information

Further information about the project, including construction photographs, is available at www.hooverdambypass.org.