Construction of the Hoover Dam Bypass

High-performance concrete used for the bridge arches

BY JEFF ST. JOHN

Since its completion in the 1930s, the roadway on top of the Hoover Dam has been a primary traffic route across the Colorado River. Increasing traffic and tourism often led to lengthy delays. Traffic volumes increased even more when U.S. 93 became a North American Free Trade Agreement corridor in the 1990s. Security concerns in the wake of the 9/11 attacks caused truck traffic to be banned from using the crossing. All of these factors motivated the design and construction of the Hoover Dam Bypass with its centerpiece river crossing, the Mike O'Callaghan–Pat Tillman Memorial Bridge.

By 2004, the Central Federal Lands Highway Division of the Federal Highway Administration had led the development of a design and the project was put out to bid. The Obayashi/PSM joint venture (JV) was awarded the contract in October 2004 with the low bid of $114 million. In early 2005, the construction team began assembling on the project site. Working near the Hoover Dam—arguably one of the 20th century's greatest engineering feats—prompted many questions about its construction: How did they handle the intense heat of a site where temperatures approach 130°F (54°C)? How did they get the workers, equipment, and materials to the site? Our team would face many of the same challenges 70 years later.

One challenge dwarfed all others: how to build the concrete arches. Our main concern was the concrete itself: mixture proportions, thermal control, concrete delivery and placement, consolidation, and possibly the chief concern—quality control.

DESIGNING THE MIXTURE

Development of the mixture proportions began 2 years before the first arch segment was cast. Many of the requirements for this high-performance concrete had been established by the design and ownership team. They included strength, aggregate selection, and thermal control requirements. Our construction team added several others to overcome delivery and placement challenges (pumpability, flowability, and long set time) and rapid strength gain to minimize form traveler cycle time.

The design strength of the concrete was 10,000 psi (69 MPa) in 56 days. The owner, the Central Federal Lands Highway Division of the Federal Highway Administration, had undertaken a detailed study of local aggregates to ensure a high-strength concrete with low permeability and low specific creep. These studies validated the design basis of the structure and reduced the amount of mixture verification required.

The specifications for the project included detailed thermal control requirements for mass concrete (primarily 4000 psi [28 MPa] concrete in the footings and 6000 psi [41 MPa] concrete in the pier caps) and also for the high-strength concrete in the arches. Figure 1 shows a typical bridge cross section. These requirements included a maximum allowable internal temperature of 155°F (68°C), and a maximum allowable temperature differential of 35°F (20°C), unless an alternate plan using an approved computer model was approved.

Operationally, we needed to achieve early strengths of 4000 psi (28 MPa) for form stripping and traveler launching and 6000 psi (41 MPa) for stressing post-tensioning tendons and erection stays. Our goals were 4000 psi (28 MPa) in 12 hours and 6000 psi (41 MPa)in 24 hours. The target slump at point of placement was 8 to 10 in. (203 to 254 mm) due to the difficult placement and consolidation conditions. Our target for setting time was at least 3 hours to allow for placing or delivery equipment failures.

Ryuichi Chikamatsu from Obayashi's Technical Research Institute in Japan consulted on the mixture proportioning. Paul Jordan of Sika Corporation lent his advice and helped with numerous trial batches. Wilbert Langley of W.S. Langley Concrete & Materials Technology, Inc., Halifax, NS, Canada, also consulted on the mixture proportioning and the thermal control requirements.

The mixture design met all of the criteria. Short- and long-term strength targets were met by a high cementitious material content (800 lb [363 kg] of cement and 200 lb [91 kg] of fly ash per cubic yard) and a very low water-cementitious material ratio (less than 0.31), typically

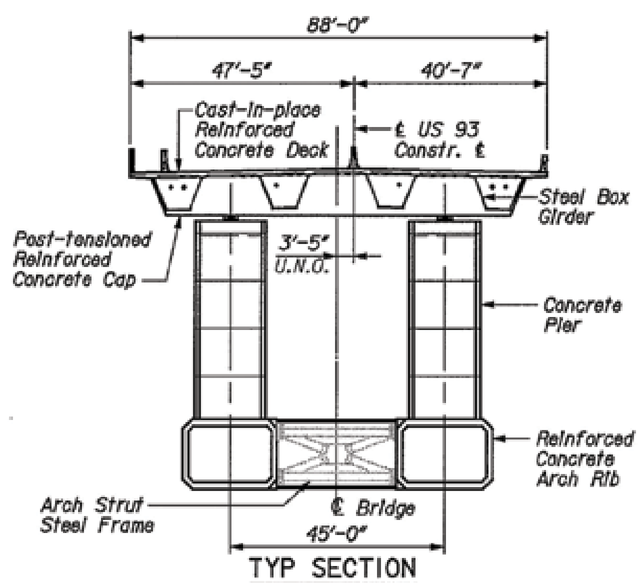

Fig. 1: A typical bridge cross section (Note: 1 ft = 0.305 m; 1 in. = 25.4 mm) *(illustration courtesy of FHWA)*

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Fig. 2: Liquid nitrogen being injected into a concrete truck *(photo courtesy of Obayashi/PSM JV)*

Fig. 3: The concrete slickline wrapped in burlene. Soaker hoses inside the burlene delivered chilled water to the exterior of the slickline in an effort to reduce concrete heat gain during pumping *(photo courtesy of Obayashi/PSM JV)*

Fig. 4: Concrete truck discharging into the concrete pump *(photo courtesy of Obayashi/PSM JV)*

achieving strengths of 4000 psi (28 MPa) in just over 12 hours (during the summer) 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 slumps exceeding 10 in. (250 mm). During our extensive trial batch process, it was observed that segregation could occur if the slump approached 11 in. (280 mm); thus, the slump was continuously monitored by our Batch Plant Operator and Quality Control Manager. Setting times in excess of 2-1/2 hours were achieved using a retarder.

COOLING

The very rich concrete mixture, however, did have a negative aspect. Without mitigation efforts, the internal curing temperatures of the concrete would have exceeded 190°F (88°C), far above the 155°F (68°C) limit specified by the contract. Mitigation methods—such as using chilled batch water or ice chips, shading the aggregate stockpiles, and placing at night—couldn't come close to reducing the maximum curing temperature to within the target range. Only two realistic options remained: circulating cold water through pipes embedded in the concrete or cooling the concrete with liquid nitrogen.

Miles of cooling tubes had been used to control temperatures during the construction of the Hoover Dam. Cooling tubes were also used for much of our bridge's substructure and pier caps. Unfortunately, for construction of the arches, the location, cycle time, installation, repair, and maintenance issues involved with cooling tubes ruled them out. Only the liquid nitrogen option remained.

The injection of liquid nitrogen into the concrete truck mixing drums shortly after batching (Fig. 2) allowed us to reduce the temperature of the concrete during the summer from 85°F (29°C) to 40°F (4°C). The initial temperature at point of placement was about 60°F (16°C), resulting in peak curing temperatures of less than 150°F (66°C). During the southern Nevada summer, the cost of the nitrogen required for cooling often exceeded $100 per cubic yard. These costs were mitigated, however, by the minimal effort needed at the point of placement and during the initial curing period. No maintenance (such as water supply or form insulation) or mitigation (grouting of cooling tubes or leaving forms in place for an extended duration) was required.

The precooling results in a "cool-and-forget" product and—with the unique structure and difficult access—offered the only viable option. An additional benefit of the nitrogen cooling is that it likely helped prevent problems with the placement system and consolidation efforts during the very warm summer months, when even at night, temperatures did not always fall below 100°F (38°C). During the hottest portions of the summer, it was necessary to precool the concrete pumping slickline by

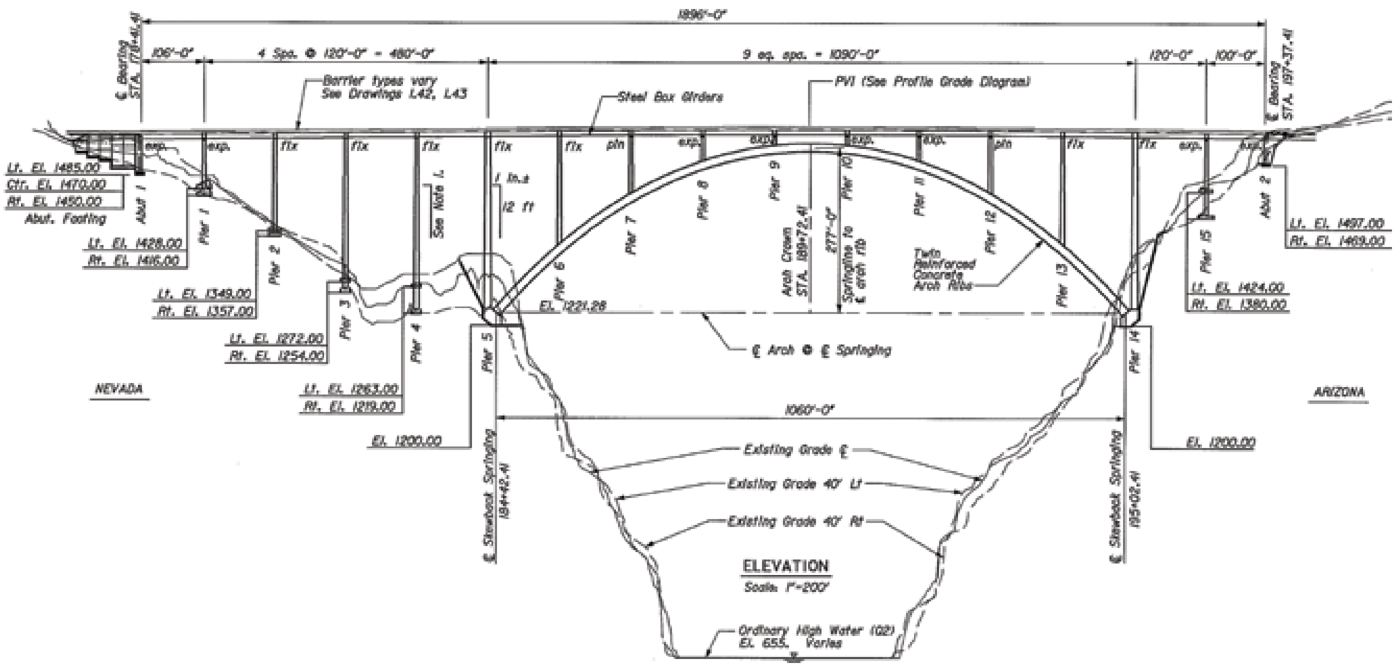


Fig. 5: Elevation drawing of the bridge (Note: 1 ft = 0.305 m; 1 in. = 25.4 mm) *(illustration courtesy of FHWA)*

filling it with chilled water prior to placement and also wrapping it with burlene soaked with chilled water to reduce heat gain through the placement system (Fig. 3).

PLACEMENT

Two options were apparent to get the concrete to the point of placement: use of a pumping system or delivery by cableway (hi-line) concrete bucket. Delivery by bucket to the point of placement (the same methodology used for construction of the Hoover Dam) was rejected to avoid tying up critical resources for several hours nearly every day and also due to the size of buckets required to maintain precise control of discharge into a very small target area (placement windows in the arch cover forms). The decision was made to use a concrete pumping system (Fig. 4).

Challenges for pumping included the harsh aggregates of the concrete mixture, the long slickline to be pumped through, the means to place in the restricted placement windows previously mentioned, 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 near the arches and the concrete could be delivered by truck. The Arizona side, with its tremendously steep cliffs, was another story (Fig. 5). There, the trailer pump was set up on the base of the arch in conjunction with a 5 yd^3 (3.8 m^3) remixer. Concrete was discharged from the delivery truck into 8 yd^3 (6 m^3) concrete buckets supported by the cableway, lowered to the base of the arch, and then discharged into the remixer. Use of the remixer allowed the buckets to be rehoisted nearly immediately to receive the next load of concrete. Tying up the cableways for half of the arch placements was a significant issue, but no other realistic option was discovered.

Fig. 6: A view up the Arizona-side cantilevers. The concrete slickline can be seen just off-center of the cantilever on the right *(photo courtesy of Obayashi/PSM JV)*

From the trailer pump, the concrete was pumped up the arch through a 5 in. (127 mm) diameter heavy wall slickline (Fig. 6) up to 600 ft (185 m) horizontally and 250 ft (77 m) vertically to a 32 m (105 ft) placing boom

Fig. 7: (a) The placing boom and platform on the Nevada-side arch cantilevers; and (b) placing boom being relocated *(photos courtesy of Obayashi/PSM JV)*

(Fig. 7) mounted atop the arch near the form traveler. The placing boom allowed precise control of discharge. A typical arch segment placement took 4 to 5 hours. All major concrete placements took place at night (Fig. 8) to avoid delivery delays due to traffic. During the warm months (April through October), this was also a requirement of the thermal control plan.

CONSOLIDATION AND QUALITY CONTROL

Consolidation of the concrete in the forms was another major concern. The geometry of the arch (many segments were placed at 45-degree angles) required the use of top surface forms for all placements. Placement windows were established in the cover forms, not only for placement, but also to allow use of high-cycle concrete vibrators. In addition, external vibrators were mounted under the bottom soffit and along the sides

ARCH SPAN DESIGN

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 comprises eight separate and significant bridges, including the centerpiece Colorado River Bridge at the Hoover Dam. 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.

HPC was the designer's focus from the beginning, according to David Goodyear, Senior Vice President, T.Y. Lin International (from *HPC Bridge Views*, September/October 2010, Issue 63). 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 the Hoover Dam, the arch span required more than just strength. Several aspects of design were controlled by both immediate and time-dependent arch deflections. So, the stiffness of HPC surpassed strength in importance.

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 mixture design work under the construction contract.

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 geometry also affected the earthquake response of the arch ribs, allowing a more flexible framing system with greater deformation along the bridge. The period of response was therefore increased and the seismic demands were reduced. The reduced seismic demands are most significant at the arch springing, where traditional arch rib design would require 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.

Fig. 8: A typical night-time concrete placement on the arches using the placing boom *(photo courtesy of Obayashi/PSM JV)*

Fig. 9: An overview of the nearly completed bridge on August 20, 2010 *(photo courtesy of Obayashi/PSM JV)*

to improve consolidation. Very little honeycombing was observed when forms were removed.

As mentioned previously, quality control was our greatest concern. One bad load of concrete could plug up the placement system and lead to a half-completed segment that would need to be removed. In addition, if a load of concrete failed to reach the required strength, we might not find out until several additional segments had been cast. The implications for cost and schedule would be staggering. Thus, our quality control efforts needed to go far beyond the usual industry standard.

Our experience with the footing construction demonstrated that traditional ready mixed concrete batching methods would not meet our quality requirements for the arch. There were too many sources of variability, such as the batching efficiency of the truck's mixing drum and the drive time. We elected to purchase a portable batch plant incorporating a 5 yd^3 (3.8 m^3) pan mixer for the project site.

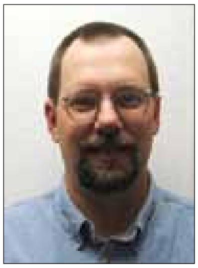
Pan mixers use high-speed paddles to mix the concrete prior to discharge into the truck. Although they are traditionally used only in precast yards, they were perfect for our application, where quality—not production rate—was paramount. The Batch Plant Operator was able to maintain the slump of the concrete within ±1/2 in. (±13 mm) during a placement. Our Quality Control Manager checked the slump of every load of concrete prior to sending it to the job site. Every third truck was tested at the job site prior to pumping. The proximity of the plant to the site made it extremely easy to make adjustments during a placement.

The result of all of these efforts can be seen in the finished structure (Fig. 9), which opened to traffic on October 19, 2010. No delays were encountered during arch construction due to pumping or placement, nor were any quality problems encountered. The arch construction actually went faster than anticipated and resulted in a monument that rivals the beauty of its neighbor.

Selected for reader interest by the editors.

PROJECT CREDITS

Owner: Central Federal Lands Division, Federal Highway Administration
Design Team: T.Y. Lin International, HDR Engineering, and Sverdrup Civil, Inc.
General Contractor: Obayashi Corporation/PSM Construction USA, Inc., a JV partnership
Concrete Suppliers: Obayashi/PSM JV for the twin arches and superstructure; Casino Redi-Mix and Silver State Materials for foundations and precast column segments
Concrete Admixture Supplier: Sika Corporation
Post-Tensioning Supplier: Schwager-Davis
Bridge Bearings: R.J. Watson



ACI member **Jeff St. John** was the Engineering Manager, and later the Project Manager, for the Obayashi/PSM JV, the general contractor of the Mike O'Callaghan–Pat Tillman Memorial Bridge over the Colorado River at the Hoover Dam. He is currently the Engineering & Planning Manager for Shimmick/Obayashi, the general contractor for the Phase IIIA seismic retrofit of the Golden Gate Bridge in San Francisco. St. John received his BS in civil engineering from Southern Illinois University, Carbondale, IL. He is a licensed professional engineer in Illinois and a member of the American Society of Civil Engineers and the American Segmental Bridge Institute.