Taking Ultra-High-Performance Concrete to New Heights

The Malaysian Experience

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Ultra-high-performance concrete (UHPC) was first introduced as reactive powder concrete in the early 1990s by the French contractor Bouygues.[1] When introduced, it came in two classes, Class 200 MPa (29 ksi) and 800 MPa (116 ksi). Since then, much research has been performed by the Federal Highway Administration (FHWA)[2] and researchers in other countries around the world, including Australia, Austria, Canada, Croatia, France, Germany, Italy, Japan, Malaysia, the Netherlands, New Zealand, Slovenia, South Korea, Spain, Switzerland, and the United Kingdom. In the United States, several state departments of transportation have expressed interest in using UHPC in their bridge projects, supported by FHWA research as well as that done by their local universities. Most notably, Virginia has produced I-beams with UHPC and Iowa has built two bridges with UHPC beams and one with a UHPC deck. A significant interest has recently been directed at using UHPC in longitudinal joints between precast concrete beams.

It appears that the high cost of UHPC has discouraged owners from implementing use of this outstanding material in applications beyond the initial demonstration projects, most of which had been subsidized by government technology implementation programs. The exception to this trend has been the significant success of the company DURA Technology (DURA) in Malaysia. Over 70 bridges have been built by DURA in that country since 2010. This article provides a summary of the steps taken by DURA to develop solutions with UHPC that are cost-effective on a first-cost basis. When the superior durability of UHPC is factored in, its value increases dramatically.

What is UHPC?

There is no universal definition of UHPC or even its name. It appears that a commonly used name and definition in the United States is the one introduced by Graybeal[3]: "UHPC-class materials are cementitious-based composite materials with discontinuous fiber reinforcement, compressive strengths above 21.7 ksi (150 MPa), pre-and post-cracking tensile strengths above 0.72 ksi (5 MPa), and enhanced durability via their discontinuous pore structure." In comparison, conventional concrete is without fibers and typically has a compressive strength of 4 to 10 ksi.

The ingredients of a UHPC mixture can vary. Early mixtures generally consisted of about 1200 lb/yd^3 (700 kg/m^3) of portland cement, 25% silica fume, 25% silica powder, and fine sand with maximum grain size of 0.03 in. (0.8 mm). A very low water-binder ratio of 0.16 to 0.20 was used. For flowability, a large quantity of high-range water-reducing admixture must be used. Steel fibers in the amount of about 2 to 2.5% by volume are used. The fibers are cut from very fine, 360 ksi (2500 MPa) wire. Other mixtures have been developed; for example, Tadros et al.[4] report on a mixture that uses local aggregates and has a cost that is about 10% of the cost of early UHPC mixtures. However, this mixture does not strictly meet the definition of UHPC because the compressive strength is only 18 ksi (124 MPa).

Factors Inhibiting Widespread Use of UHPC

The original prebagged UHPC product introduced to the U.S. market had tight tolerance specifications. The steel fibers had to be imported from abroad, which required a waiver of Buy America requirements for many projects. As a result, the unit cost was relatively high. In addition, the UHPC was expected to be mixed in high-energy mixers for 8 to 17 minutes, plus another 10 min. for loading the mixer and unloading the mixture into a ready-mix truck or other transportation devices. However, Graybeal[3] has reported that mixing of UHPC can be performed using conventional mixers, as long as high energy input is provided. Temperature of the mixture, due to increased mixing time, can be controlled through use of ice water. The steel fibers are now available from a manufacturer in the United States.

Upon placement, the early development of UHPC called for curing for at least 48 hours at a high, 90°C (194°F), temperature. Some of the original mixtures were also required to be cured in high-pressure chambers. This is inconsistent with standard practice of 12- to 16-hour, overnight curing with maximum temperatures of 70°C (158°F). Loss of productivity and high materials costs could result in a premium of 400% or more of the cost of conventional concrete. This sharp increase cannot be offset by the anticipated reduction in total quantities. Wille et al.[5] have demonstrated that an optimized mixture can achieve the required strength without the originally required heat or pressure curing.

An effort is urgently needed in the United States to publish American Association of Highway and Transportation Officials (AASHTO) specifications for design and construction with UHPC. Australia, France, Japan and most recently Switzerland have already published design recommendations and model code language.

The Malaysian Experience

Introduction of UHPC in Malaysia was started by a couple of engineers in 2006. The company DURA was co-founded by Dr. Yen Lei Voo after he completed his Ph.D. in Australia on the topic of UHPC. His advisor was Professor Stephen Foster, who had been championing UHPC in Australia. Interestingly, the use of UHPC in Australia has stagnated since the construction of its first bridge, the Shepherd Gully Creek Bridge,

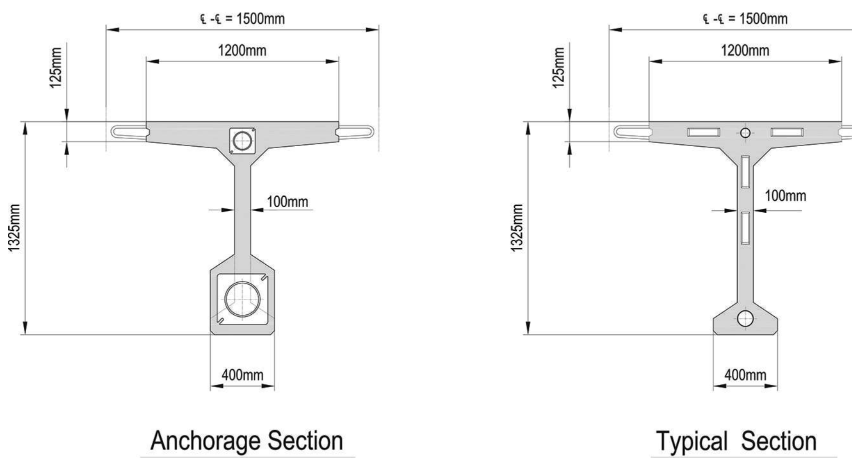

Figure 1. Decked bulb-tee section used in the Sungai Nerok Bridge. All Figures and Photos: DURA Technology. Note: 1 in. = 25.4 mm.

in 2003. The initial Australian experience has paralleled that in the United States and Canada where small demonstration projects did not create the anticipated acceptance. DURA's pioneers started with an intensive research program from 2006 to 2010, supported by the Malaysia Public Works Department. The research program yielded important optimization factors:

- The constituent materials were reduced to cement, silica fume, sand, high-range water-reducing admixture, and water. Further, relatively low-cost steel fibers were identified. As a result, the original \$2600/m^3 (\$2000/yd^3) cost was reduced to about \$600/m^3 (\$460/yd^3).

- A large, 12 m^3 (15.7 yd^3) single shaft ribbon blender was used for mixing powder and highly viscous materials. The precast concrete product was sized so that it could be produced with only one batch of UHPC; piece weights were limited to about 20 tonnes (22 tons). There is no waiting for the next batch, and no concern for differential setting time, thermal gradient, or shrinkage between batches. There are counter-intuitive benefits to making relatively small pieces, such as:
    - o The UHPC is mixed in one cycle using the large mixer.
    - o The precast elements can be made in a small, indoor facility.
    - o The precast elements can be shipped in enclosed trucks and shipping containers.
    - o The precast elements can be handled at the jobsite with small equipment.

- Four standardized cross-section shapes were created: pretensioned decked I-beams for short spans, spliced I-beams and segmental U-girders for medium spans, and segmental box-girders for long spans. The longest span constructed to date is 100 m (328 ft).

Figure 2. Rantau-Siliau Bridge during construction.

- Straight pretensioning was used where possible. However, most applications involve spliced post-tensioned beams, using straight bottom flange post-tensioning. The segment interfaces are match-cast, with shear-keyed joints.

- Each UHPC batch was required to achieve a 1- and 28-day average compressive (cube) strength of 70 MPa (10 ksi) and 165 MPa (24 ksi), respectively, and for an average flexural strength at 28 days of 25 MPa (3.6 ksi).

- Most significantly, perhaps, is that curing was simplified such that the standard precast, prestressed concrete 1-day cycle is maintained. Once the strands are detensioned, the product is subjected to additional curing without losing production efficiency.

These measures have resulted in highly successful and a rapidly growing number of UHPC bridges, with lower initial cost than conventional construction and with a life expectancy far exceeding the 100 years desired by the design community. The number of completed bridges has increased from one bridge in 2010 to 2, 5, 14, 16 and 37 in 2011, 2012, 2013, 2014, and 2015, respectively. The year 2016 is expected to continue to break records with 32 bridges already completed or under construction.

Example Bridges[6]

The Sungai Nerok Bridge has three 30-m-long (98 ft) spans and is 15 m (49 ft) wide. Each span has 10 beams spaced at 1.5 m (5 ft) center to center. Each beam was made of two identical decked bulb-tee halves (Fig. 1) spliced with nineteen 0.6-in.-diameter (15.2 mm) strands in a single bottom post-tensioning tendon and four 0.6-in.-diameter (15.2 mm) strands in the top tendon. Each beam weighed 29 tonnes (32 tons). The web was only 100 mm (3.94 in.) wide. It had no reinforcing bars except at the ends in the post-tensioning anchorage zones. The longitudinal connections between flanges were made with conventional reinforcement and cast-in-place UHPC closure placements.

The Rantau-Siliau Bridge has a single span 52 m (170 ft) long and is 18.3 m (60 ft) wide. The cross section has five 1.75-m-deep (5.87 ft) U-beams (Fig. 2

and 3). The U-beam ends were encased in the conventional concrete of the integral abutments. Conventional reinforcement was used only in the anchorage zones and to connect the girders to the 200-mm-thick (7.9 in.) cast-in-place, conventional concrete deck.

Each U-beam consists of intermediate 8-m-long (26.2 ft) segments and two end segments that are 5.75 m (18.9 ft) long, weighing 18 and 16.5 tonnes (19.8 and 18.2 tons), respectively. Post-tensioning of each U-beam consisted of four bottom tendons each with twenty-seven 0.6-in.-diameter (15.2 mm) strand and two top tendons with four 0.6-in.-diameter (15.2) strand.

The record breaking 100-m-long (328 ft) bridge at Batu 6, Gerik, was completed in 2015. This segmental box-girder bridge has thirty-six 2.5-m-long (8.2 ft) standard intermediate segments and four anchorage segments (Fig. 4). The standard segment weighs 17 tonnes (18.7 tons).

Conclusion

UHPC is a fascinating new material, featuring very high compressive and tensile strengths and excellent durability. Since its introduction in the early 1990s, various countries have attempted to introduce it to bridge construction, with limited success. Initial high unit costs and perceived production and design difficulties have contributed to its slow adoption.

However, DURA in Malaysia has developed successful techniques for cost-effective solutions. By producing pieces no heavier than 20 tonnes (22 tons), reducing the precast bed production cycle to the conventional 1 day, and optimizing the UHPC mixture proportions to produce the required properties at a fraction of the cost of previous mixtures, it has been possible to build up to 70 bridges in the past 5 years.

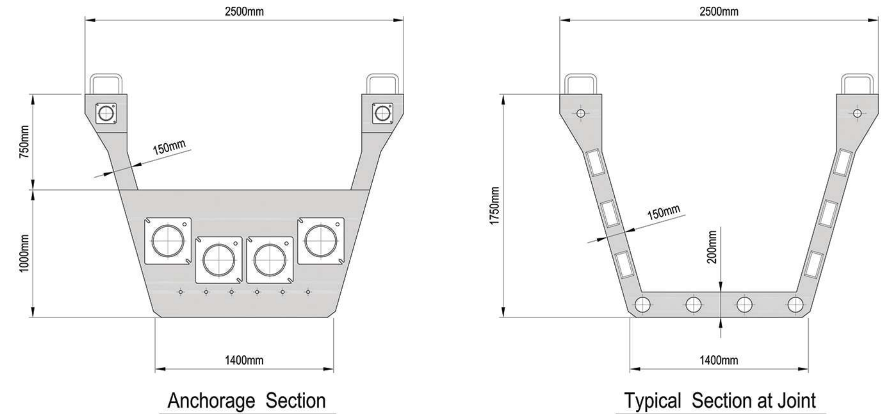

Figure 3. Details of ultra-high-performance concrete U-beams cross section.

References

1. Richard, P. and M. H. Cheyrezy. 1993. "Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength," *ACI SP-144: Concrete Technology: Past, Present, and Future*, American Concrete Institute, Detroit, MI. SP-144, pp: 507-518.
2. Russell, H. G. and B. A. Graybeal. 2013. "Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community," Publication No. FHWA-HRT-13-060, National Technical Information Service, Springfield, VA. 171 pp.
3. Graybeal, B. 2011. "Ultra-High Performance Concrete," *TechNote,* FHWA-HRT-11-038, Federal Highway Administration, McLean, VA.
4. Tadros, M. K. and G. Morcous. 2009. "Application of Ultra-High Performance Concrete to Bridge Girders," Nebraska Department of Roads (NDOR) Project Number P310, Lincoln, NE. February, 72 pp.
5. Wille, K., A. E. Naaman, and S. El-Tawil, S. 2011. "Optimizing Ultra-High-Performance Fiber-Reinforced Concrete," *Concrete International*, Vol. 33, No. 9, September, pp. 35-41.
6. Voo, Y. L., S. J. Foster, and M. F. Hassan. 2014. "The Current State of Art of Ultra-High Performance Concrete Bridge Construction in Malaysia," *Proceedings of the 12th International Conference on Concrete Engineering and Technology 2014* (CONCET 2014), Selangor, Malaysia, August 12-14, pp. 95-102.

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EDITOR'S NOTE

Further discussions with Dr. Voo reveal this type custom industrial mixer (single shaft ribbon blender) may be found at http://www.sowergroup.com/instruction_detail/&productId=115.html

Figure 4. Batu 6 segmental box-girder bridge with 100 m (328 ft) span.