Testing of Ultra-High-Performance Concrete Girders

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The next generation of high performance concrete, known as ultra-high-performance concrete (UHPC), is currently being evaluated at the FHWA's Turner-Fairbank Highway Research Center (TFHRC) Structures Laboratory, McLean, Virginia. The laboratory is testing two AASHTO Type II prestressed concrete girders fabricated from UHPC to characterize their structural behavior and determine how well the current AASHTO design provisions represent that behavior. UHPC is a steel fiber-reinforced reactive powder concrete.

This newly developed material typically reaches a compressive strength of 30 ksi (200 MPa), which is more than twice that of any high performance concrete used to date in the United States for bridge construction.

Material

The reactive powder mixture used in the test girder was developed and patented by Paris-based Bouygues, S.A., in 1995 and is being produced by Lafarge, also of Paris. The FHWA test girders, which contain a 2 percent random steel fiber content, were manufactured in three days by Prestress Services of Lexington, Kentucky and donated to the FHWA for the test. The basis for its enhanced properties is a mix design specifically engineered to produce a highly compacted concrete with a small, disconnected pore structure. This is achieved by using a combination of finely ground powders along with the elimination of coarse aggregate.

Elimination of the coarse aggregate minimizes the paste-aggregate bond-failure mechanism that limits the strength of typical high performance concretes. In addition to the portland cement, silica fume, sand, high-range water-reducing admixture, and water found in a typical high performance concrete, the UHPC mix includes fine sand, quartz flour (maximum grain size of 600 microns), and steel or organic fibers.

The quartz flour is the reactive powder from which this material draws its name. It was selected for its grain size and chemical reactivity. The quartz flour is combined with the fine sand and other components of UHPC in carefully selected proportions to ensure homogeneity of the mix. It is this homogeneity, which is the result of using components of similar size and modulus, that is responsible for many of the enhanced characteristics of UHPC.

The steel fibers used are about $^1/_2$ in. (13 mm) long and 6 mils (0.16 mm) in diameter. Depending on the application, fiber is added to the matrix in a volume proportion of 2 to 4 percent. These fibers contribute to much of the tensile strength and toughness of the material. While most high performance concretes remain almost linear-elastic up to failure, UHPC provides significant post-cracking strength due to the large number of fibers in the matrix confining the material.

The presence of the steel fibers also eliminates any need for mild reinforcing steel in the girders. That is, neither temperature and shrinkage reinforcement nor shear stirrups are fabricated into the members. With the fibers being the largest particle in the matrix, they tend to reinforce the mix on a micro level.

The placing and curing of this material can be completed using procedures similar to those already established for use with some high performance concretes. The mix is very fluid and is virtually self-placing requiring no internal vibration. External form vibration causes the mix to behave fluidly, smoothly flowing into place.

After an initial setting time of 24 hours, the curing process takes at least an additional 48 hours. Complete curing of the concrete is achieved by subjecting the girders to a vapor bath at a constant 190°F (88°C) temperature during that time period. Once the curing process is completed, the material will have stabilized and achieved its full strength. Further creep and shrinkage of the concrete is practically eliminated by a complete cure.

Testing

The main thrust of the first structural test at the TFHRC was to determine the flexural capacity of an 80 ft (24 m) long AASHTO Type II girder fabricated with UHPC and 26 – $^1/_2$ in. (13 mm), 270 ksi (1860 MPa) low-relaxation prestressing strands. Initial cylinder and

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In the laboratory, the UHPC girder deflected approximately 12 in. (305 mm) without showing any visible cracks.

prism testing was conducted prior to the flexural test to establish a limited number of material properties. These component tests indicated that the UHPC girder had a compressive strength of 190 MPa (27.5 ksi), a modulus of elasticity of 8 ksi (55 MPa) and a modulus of rupture of 2.4 ksi (16.5 MPa).

For the flexure test, load was applied at two points, 6 ft (1.8 m) apart, centered on the midspan of the girder to create a constant moment region. The girder was tested using increments of load in the elastic range and increments of displacement in the inelastic range. The girder sustained a peak-applied moment of 3225 kip-ft (4400 kN-m) before failure. This moment corresponded to a total applied load of 180 kips (800 kN) and a midspan deflection of over 19 in. (485 mm). Failure of the girder occurred when enough strain was concentrated into the prestressing strand to fracture them at the only location of gross cracking observed.

More impressive than the ultimate performance of this girder was its ability to sustain a large load and associated deflection without creep, relaxation or any visual sign of distress. The flexural test was suspended for more than 12 hours with 12 in. (305 mm) of midspan deflection locked into the girder. During that time, the reaction of the girder was unchanged. Also during this time, cracks were undetectable anywhere along the length of the girder, even with the aid of a 3x magnifying glass.

Three of four structural tests designed to determine the shear capacity of the UHPC girder have recently been completed. Two of the tests utilized each half of the fractured girder from the flexure test. The third test utilized one end of a 30 ft (9.2 m) AASHTO Type II girder.

The current philosophy in the design of typical and HPC concrete beams is that mild steel reinforcing stirrups will engage to carry shear loads once the capacity of the concrete section alone has been reached and cracking develops. Since the UHPC girders lack any form of mild steel reinforcing, the shear capacity testing is of particular interest and justifies the currently planned four tests.

In the three completed tests, the shear span-to-depth ratio ranged from 2.0 to 2.5. A single load was applied incrementally to the top of the girder until failure. The shear capacity of the section ranged from 380 to 500 kips (1700 to 2220 kN) depending on the level of prestress and other distress induced by previous testing. The shear failure of the fully prestressed section was brittle; however, the failure of the partially prestressed section and the distressed section was relatively ductile with significant shear capacity remaining after the peak shear was reached.

Conclusion

The testing to date at TFHRC has shown that UHPC is a promising material for use in the bridge construction industry. Compared to high performance concrete, UHPC exhibits greatly increased tensile strength, compressive strength and toughness, as well as significant enhancements in other important properties.

Beyond the completion of these initial tests, it is planned that a series of material tests will be conducted to evaluate the behavior of the material. Once the fundamental behavior of UHPC is understood, more efficient shapes will need to be developed to make the material a practical solution for typical bridge applications.

Postscript

The first bridge project using reactive powder concrete was a pedestrian bridge in Sherbrooke, Quebec, Canada, constructed in 1997. The bridge was manufactured in a precast operation in six segments, each 33 ft (10 m) long, transported to the site, and post-tensioned together. The bridge is a three-dimensional space truss with a clear span of 198 ft (60 m) and a top deck 1.25 in. (30 mm) thick. Further details on this project were published in the article "Precast, Prestressed Pedestrian Bridge–World's First Reactive Powder Concrete Structure," by Pierre Y. Blais and Marco Couture, in the September-October 1999 PCI JOURNAL.

Currently under construction in Seoul, Korea, is a pedestrian bridge with a clear span of 390 ft (120 m) and a structural depth of 3.6 ft (1.1 m) using a modified double bulb-tee girder with a deck thickness of 1.25 in. (30 mm).

The first vehicular bridge using the material is scheduled for construction in Australia this year. Several other bridge projects are expected to be under development in North America, Europe, Australia, and Asia.