A contribution from ACI Committee 239, Ultra-High Performance Concrete

Advancing Ultra-High-Performance Concrete

ACI Committee 239 convenes experts to deliver strategic advancements

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Over the past three decades, a wide range of ultra-high-performance concrete (UHPC) products and solutions have been researched, developed, and implemented on hundreds of structural and architectural projects in numerous countries. Extensive research took place in Europe during the 1970s and 1980s as this class of materials was initially being envisioned. By the 1990s, UHPC began to be recognized by the broader community for its combination of superior properties, including strength, ductility, durability, and aesthetics—many declared it a "revolutionary new material" for the construction industry. Because of these combined properties, it has since been determined that UHPC is highly suitable and adaptable for a vast range of precast or field-cast applications, including structural elements, field-cast connections, and architectural elements such as façades and rainscreens. A significant number of UHPC projects now have more than 10 years of in-service performance, thereby validating these superior capabilities and providing added value to stakeholders.

As owner expectations for durable, sustainable construction materials and structures continue to increase, so does the demand for UHPC solutions. In North America alone, more than 300 bridges now have UHPC elements or connections, with the majority constructed during the past 5 years. This trend toward the use of durable, resilient constructed solutions is expected to grow in the years ahead, and UHPC is well positioned to fill the need.

When developing a new class of materials for the construction industry, it is critical to develop a community of well-advised experts who are capable of appropriately framing discussions concerning material capabilities, performance characteristics, applications, and potential benefits. Such expertise is necessary if an innovative solution is to move from laboratory concept to broad use within the public and private sector construction environments.

UHPC pi-girder bridge, Buchanan County, IA
(photo courtesy of Ben Graybeal)

In 2011, ACI's Technical Activities Committee (TAC) approved formation of ACI Committee 239, Ultra-High Performance Concrete, focused specifically on developing and reporting information on UHPC. The main committee has four active subcommittees, tasked with the consolidation and dissemination of information on specific UHPC topics: 239-A, Emerging Technology Report; 239-C, Structural Design of UHPC; 239-D, Materials and Methods of Construction with UHPC; and 239-E, Educational Outreach. Altogether, 14 voting members, three consulting members, 72 associate members, and numerous friends of the committee with expertise in UHPC, concrete, and engineering support the work of ACI Committee 239.

What is UHPC?

UHPC is defined as: "concrete that has a minimum specified compressive strength of 150 MPa (22,000 psi) with specified durability, tensile ductility, and toughness

Table 1:
Material characteristics of conventional concrete and UHPC[1]

Material characteristic	Conventional concrete	UHPC
Compressive strength, psi (MPa)	3000 to 6000 (20 to 40)	22,000 to 36,000 (150 to 250)
Direct tensile strength, psi (MPa)	150 to 440 (1 to 3)	900 to 1700 (6 to 12)
Elastic modulus per ASTM C469/C469M,[2] psi (GPa)	3,600,000 to 4,400,000 (25 to 30)	6,000,000 to 7,200,000 (40 to 50)

Table 2:
Properties of conventional concrete versus UHPC[1]

Properties	Conventional concrete	UHPC
Geometrical	Particles and aggregates are various sizes	Requires a limitation of aggregate size typically < 0.6 mm (0.02 in.) and limited sand dosage
Mechanical	Stiffness difference between aggregates and cement paste	Enhancement of paste properties with an elastic modulus closer to the sand skeleton
Chemical	Chemical shrinkage of the paste inside a rigid skeleton of aggregates (more damage)	Paste content sufficient between aggregates to avoid rigid skeleton. Self-desiccation shrinkage is not blocked (less damage)

requirements; fibers are generally included to achieve specified requirements."[1] Some jurisdictions, such as Canada and Switzerland, set a lower limit for the minimum compressive strength (120 MPa [17,000 psi]).

UHPC typically consists of cement, silica fume, fine quartz sand, high-range water-reducing admixtures, and fibers. It has a low water-binder ratio (*w/b*), usually ranging between 0.15 and 0.25. Multiple variations of UHPC matrices also have been developed that contain other supplementary cementitious materials and/or coarse aggregates.

Reinforced with steel or organic fibers (depending on the application), UHPC is fundamentally different from conventional concrete because it offers sustained, post-cracking tensile resistance and can be detailed to deliver a ductile tensile and flexural response. The disconnected pore structure within the UHPC cementitious material matrix also differs from conventional concrete, with extremely low permeability resulting in improved resistance to chemicals, freezing and thawing, carbonation, and chloride ion penetration. Furthermore, UHPC has a higher elastic modulus than conventional concrete. Table 1 provides typical ranges for selected mechanical properties of conventional concrete and UHPC, while Table 2 presents specific geometrical, mechanical, and chemical properties of conventional concrete versus UHPC.

In addition to greatly reduced maintenance requirements and extended usage life, these properties allow increased speed of construction as well as elimination of additional reinforcement and post-tensioning. Two notable examples of the engagement of these benefits to address end user needs are prefabricated system connections and precast architectural wall panels.

Field-cast UHPC connections for prefabricated components address a traditionally weak link in infrastructure construction by simplifying construction and significantly delaying any connection-based deterioration. The use of UHPC in architectural wall panels facilitates multiple improvements: the ability to produce more complex, lighter, thinner, more robust elements (compared to conventional concrete panel systems); the look and feel of concrete in a vast range of textures and colors; improved energy efficiency; and the exceptional durability that comes from this class of materials.

Given that UHPC is a class of cementitious materials, mixture formulations often make trade-offs to enhance one property while detracting from others. The main characteristics of UHPC are achieved through these main principles[3]:

- Homogeneity enhancement by eliminating coarse aggregates in the matrix;
- Density enhancement by optimizing the packing density of the matrix (achieved through optimizing gradation and mixture proportions between the main matrix constituents); and
- Ductility enhancement by introduction of fibers. As the matrix is very brittle, fiber reinforcement is added to obtain elastic-plastic or strain-hardening behavior in tension. Typically, UHPC has a fiber content of 2% or more by volume. The maximum fiber content is a function of the

I-81, Syracuse, NY: (a) field-casting of UHPC on an interstate bridge construction project; and (b) UHPC connection between precast deck panels and between panels and the girder *(photos courtesy of Ben Graybeal)*

fiber aspect ratio and shape as well as production issues, such as workability.

A wealth of technical knowledge on UHPC materials and performance is available in the research literature. As a starting point, readers are encouraged to consult "Ultra-High-Performance Concrete: An Emerging Technology Report (ACI 239R-18)."[1] This document, the first formal publication from ACI Committee 239, is intended to raise awareness of the performance and potential value of UHPC.

Materials and Methods of Construction

Because UHPC contains different constituent proportions and offers different performance attributes than conventional concrete, it is not surprising that concrete experts would need guidance on the materials and methods of construction commonly associated with UHPC. ACI Subcommittee 239-D has therefore embarked on a major effort to develop and report the needed guidance that will address constituents and mixture proportioning, and fresh and hardened properties. It will also cover construction activities such as placement methods, formwork, curing, quality control, test methods, and repair. This information will be of immediate practical value to anyone associated with the use of UHPC.

The practical use of UHPC has also been significantly assisted by the publication of ASTM C1856/C1856M.[4] Although it is possible to use existing standardized fabrication practices and test methods to assess most properties of UHPC, these practices and methods were developed for conventional concrete and thus might not align with the state-of-the-practice for UHPC-class materials. ASTM C1856/C1856M builds off existing standards, giving users a comfortable starting point to then begin working with UHPC. The standard addresses the sampling and testing of fresh UHPC, fabrication of test specimens, and execution of hardened specimen tests for properties including compressive strength, modulus of elasticity, creep, and resistance to freezing and thawing.

Structural Design of UHPC

With UHPC structural design guidance already available in Europe, Asia, Canada, and Australia, it is time for the U.S. community to push forward with the development of guidance that aligns, complements, and extends existing standards and practices. ACI Subcommittee 239-C is leading this effort within the Institute and has been authorized to develop a

Global Knowledge Sharing

The Second International Interactive Symposium on UHPC
June 2-5, 2019, Albany, NY, USA

Several members of ACI Committee 239 are actively involved in the organization of the Second International Interactive Symposium on UHPC. Building on the success of the first symposium in 2016, this event will bring together the international UHPC community for learning, networking, and advancement. This interactive symposium will allow UHPC professionals to:

- Share knowledge about applications and opportunities;
- Broaden technical depth;
- Identify knowledge gaps; and
- Grow the UHPC family dedicated to truly working together to achieve similar goals.

For more information, visit **www.register.extension.iastate.edu/uhpc2019**.

report that documents the current state-of-the-art in structural design guidance for UHPC elements. It is expected that the report will be fully drafted in 2019, marking a critical step toward the eventual development of formal design guidance in the United States.

Separately, efforts within the U.S. Federal Highway Administration (FHWA) are also underway to develop structural design guidance for UHPC. The highway bridge sector has been a strong early adopter of UHPC solutions; however, lack of formal design guidance has hindered some applications. Working with relevant technical committees in the American Association of State Highway Transportation Officials (AASHTO), FHWA is drafting an AASHTO Guide Specification on the Design of UHPC with the intent of shepherding it toward AASHTO balloting in 2 years. This document will address many of the needs of bridge owners and designers, and provide the broader U.S. community with a domestic reference from which further development can occur.

Educational Outreach

The newly formed ACI Subcommittee 239-E is tasked with raising awareness and educating the broader community about UHPC. With implementation of any new material in the construction sector, one of the most significant hurdles is the creation of a large community of practice that understands the successful applications, limit states, and potential value of the material. The subcommittee anticipates it will develop and deliver web-based and classroom-based content that introduces UHPC and provides a solid baseline of knowledge to any interested party. By compiling and sharing knowledge with the industrial, consulting, and academic communities, this subcommittee will open doors to further innovation as UHPC technology continues to be applied to an ever-wider array of existing challenges.

Looking Ahead

ACI Committee 239 is also informally working on a suite of emerging ideas for the future use of UHPC products and solutions, each of which addresses a key need in the sector. Given that UHPC is different from conventional concrete, there is clearly a need for certified "UHPC Ready" concrete field technicians. As such, the committee has begun discussions to determine the content and training that will be needed. It is also working toward the identification of research requirements that will help the research community to use their resources and skill sets to advance the state-of-the-art. Lastly, the committee has instituted a formal process to vet and endorse relevant research proposals that are applying to

Post-tensioned UHPC channel girder in the MuCEM pedestrian bridge, Marseille, France *(photo courtesy of Ben Graybeal)*

Precast deck panel placement prior to UHPC connection casting, Pulaski Skyway, NJ *(photo courtesy of Ben Graybeal)*

receive ACI Foundation Concrete Research Council funds.

Conclusions

Considering the overall history of concrete, UHPC is still a very young material. Today, hundreds of completed UHPC projects exist worldwide. They are performing as expected and demonstrate how the technology can provide value while meeting the needs of owners and end users. Many of these projects now offer more than 20 years of in-service data, further validating the material performance and proving that UHPC technology is working and evolving.

ACI Committee 239 has become a convening point for national and international experts in the field of UHPC. As the technology becomes more widely known and engaged, there will be a significant, growing need for knowledge and expertise to support increasingly sophisticated constructions. It is anticipated that the forum provided by ACI and fed by the passion of the committee members will continue to address these needs for years to come.

For more information about ACI Committee 239, visit **www.concrete.org/committees/directoryofcommittees/acommitteehome.aspx?committee_code=C0023900**.

Precast deck panel placement prior to UHPC connection casting, Franklin Avenue Bridge, MN *(photo courtesy of Ben Graybeal)*

References

1. ACI Committee 239, "Ultra-High-Performance Concrete: An Emerging Technology Report (ACI 239R-18)," American Concrete Institute, Farmington Hills, MI, 2018, 21 pp.

2. ASTM C469/C469M, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," ASTM International, West Conshohocken, PA.

3. Richard, P., and Cheyrezy, M., "Composition of Reactive Powder Concretes," *Cement and Concrete Research*, V. 25, No. 7, Oct. 1995, pp. 1501-1511.

4. ASTM C1856/C1856M, "Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete," ASTM International, West Conshohocken, PA.

Selected for reader interest by the editors.

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