Ultra-High-Performance Concrete: An Emerging Technology Report

Reported by ACI Committee 239

ACI 239R-18

Emerging Technology Series

American Concrete Institute
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First Printing
October 2018
ISBN: 978-1-64195-034-3

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This emerging technology report gives an overview of ultra-high-performance concrete. It briefly introduces the production of these concretes, their properties, design principles for their use, and example applications. It is not intended to be an exhaustive document, but rather to serve as a starting point for the concrete practitioner on understanding this class of materials.

Keywords: applications; ductility; durability; fiber-reinforced concrete; ultra-high-performance concrete.

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ACI 239R-18 was adopted and published October 2018.

CHAPTER 1—INTRODUCTION AND SCOPE

Ultra-high-performance concrete (UHPC) is a class of advanced cementitious materials with greater strength, tensile ductility, and durability properties when compared to conventional or even high-performance concrete. For the purposes of this document, UHPC is limited to concrete that has a minimum specified compressive strength of 22,000 psi (150 MPa) with specified durability tensile ductility and toughness requirements; fibers are generally included to achieve specified requirements. UHPC typically exhibits elastic-plastic or strain-hardening characteristics under uniaxial tension and has a very low permeability due to its dense and discontinuous pore structure.

1.1—Introduction

UHPC typically consists of cement; silica fume; fine quartz sand; high-range water-reducing admixtures; and fibers with water-binder ratios (*w*/*b*) usually ranging between 0.15 and 0.25. However, multiple variations of UHPC matrixes have been developed that contain other supplementary cementitious materials and sometimes coarse aggregate. Alternate formulations often make trade-offs to achieve enhancement of one property that may negatively impact others. The main characteristics of UHPC are achieved through the following three principles (Richard and Cheyrezy 1995):

1. Homogeneity enhancement by eliminating coarse aggregates in the matrix
2. Density enhancement by optimizing the packing density of the matrix; this is achieved through optimizing gradation and mixture proportions between the main matrix constituents
3. 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 fiber contents of 2 percent or more by volume. The maximum fiber content is a function of the fiber aspect ratio and fiber shape as well as production issues such as workability.

UHPC development originated with studies on high-strength cement pastes with low water-cementitious materials ratios (*w*/*cm*) of 0.20 to 0.30 by Yudenfreund et al. (1972a,b,c), Odler et al. (1972a,b), and Brunauer et al. (1973a,b). These pastes had low porosity leading to compressive strengths up to 29 ksi (200 MPa) and low dimensional changes. Strength enhancement by hot pressing techniques was first applied by Roy and Gouda (1973) and Roy et al. (1972) and resulted in very-high-strength cement pastes with compressive strengths up to 98 ksi (680 MPa). With the development of high-range water-reducing admixtures and pozzolanic admixtures such as silica fume, two kinds of materials emerged in the 1980s. Polymer-modified cementitious materials called macro-defect-free (MDF) concretes had a compact matrix but were susceptible to deterioration by water and had high creep due to the presence of certain polymers (Kendall et al. 1983; Alford and Birchall 1985). Densified systems containing homogeneously arranged ultrafine particles (DSP) used the interaction of high-range water-reducing admixtures and silica fume to decrease the porosity of the material and to increase the strength. DSP still exists and was the basis for modern UHPC development (Bache 1987). The density of the matrix of UHPC mixtures was theoretically investigated and optimized (de Larrard and Sedran 1994). The brittleness of the matrixes was recognized, and various combinations of steel and synthetic fibers were used to increase ductility of the materials (Richard and Cheyrezy 1995; Bache 1987).

The first commercial applications of UHPC started in the 1990s in Europe and has spread worldwide. Several major research programs on UHPC have been carried out worldwide, such as early research in France and Japan, resulting in code-style guidelines (AFGC 2002; Japanese Society of Civil Engineers 2008), a large federally funded program in Germany (Schmidt 2008), as well as several research programs in Canada and the United States (Russell and Graybeal 2013; Graybeal 2011). UHPC has been used in multiple applications such as bridges and infrastructure, facades, buildings, elements in aggressive environments, and for security and blast resistance. Applications include new construction and rehabilitation using both cast-in-place and precast UHPC components. UHPC in its present form became commercially available in North America in approximately 2000.

1.2—Scope

UHPC is still in the process of finding a broader use. The objective of this report is to introduce UHPC through a brief overview of production, properties, design, and applications, and to promote further use of UHPC and integration into today's construction market. Because the cost of UHPC is high when compared to conventional concrete, use should be focused toward applications that engage several of the exceptional properties of the material. Current research needs have been identified as improved design guidance, standardization, and broader material knowledge.

CHAPTER 2—DEFINITIONS

2.1—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

conventional concrete—concrete that has a specified compressive strength for design of less than 8000 psi (55 MPa).

strain hardening—ability to carry increasing tensile load beyond the point of first crack.

strain softening—ability to carry a reduced (but nonzero) tensile load beyond the point of first cracking.

ultra-high-performance concrete—concrete that has a minimum specified compressive strength of 22,000 psi (150 MPa) with specified durability tensile ductility and toughness requirements; fibers are generally included to achieve specified requirements.

CHAPTER 3—PRODUCTION

3.1—Materials

The materials used to make ultra-high-performance concrete (UHPC) are similar to those commonly found in traditional concrete. Constituent materials are selected based on their particle size to optimally pack the matrix to reduce voids between the particles. While some commercially available UHPC mixtures are proprietary, with their exact composition not reported, other mixture compositions are readily available. Some mixtures feature less common components such as silica flour, which is silica sand ground to achieve a specific particle size. The addition of high-strength steel fibers to the matrix results in improved ductility and the ability to eliminate some of the mild steel reinforcement normally found in conventional reinforced concrete members (Graybeal 2006a).

3.2—Mixture proportioning

The high strengths and superior performance achieved with UHPC stem from the reduction of void space in the matrix and discontinuous pore structure, depending more on the material's behavior on a microscopic level than on the properties of its constituent components. Through the proper selection of components based on both their particle size and mechanical properties, the number of contact points between particles is increased, which in turn causes the level of stress transferred between particles through the paste to be reduced and less variable. This reduction and more even distribution of forces alleviates the formation of microcracks in the matrix and ultimately results in improved mechanical properties. Table 3.2 depicts two representative mixture proportions for UHPC and demonstrates how the mass proportions can vary based on the particle sizes.

Table 3.2—Two possible UHPC mixture proportions by mass

UHPC component	Mixture Proportion 1	Mixture Proportion 2
Cement	1	1
Silica fume	0.325	0.389
Sand	1.432	0.967
Quartz powder/silica flour	0.300	0.277
High-range water-reducing admixture	0.027	0.017
Water	0.280	0.208
Steel fibers	0.200	0.310

Note: Mixture Proportion 1 is from Bonneau et al. (1996). Mixture Proportion 2 is from Williams et al. (2009).

The matrix of UHPC is optimized for particle packing, that is, the mixture proportions of typical components such as sand, silica fume, and cement are optimized to achieve the densest packing possible, as investigated by de Larrard and Sedran (1994). Another unique aspect of UHPC is that some cementitious material particles may not take part in the hydration process, but merely serve as fine aggregate in the overall matrix. It is common for 30 to 50 percent of the cement to be hydrated in UHPC due to the low water content (Morin et al. 2001; Habel et al. 2006).

3.3—Mixing

UHPC has been produced using a wide variety of mixers, ranging from laboratory-sized pan mixers to revolving drum truck mixers. Mixing UHPC, in general, is a somewhat different process than mixing conventional concrete. UHPC typically includes a limited amount of water and little, if any, coarse aggregate. As such, the UHPC requires the input of extra mixing energy both to disperse the water and to overcome the low internal mixing action from the lack of coarse aggregate. A typical mixing process involves first charging the mixer with the dry components and ensuring that they are fully blended. Thereafter, the water and the liquid admixtures are added and dispersed. Mixing continues, sometimes for an extended period depending on the mixer energy input, until the UHPC changes from a dry powder into a fluid mixture. Once fluid, the fiber reinforcement (if included) is added in a deliberate manner to ensure uniform distribution through the mixture without agglomeration. After fiber dispersion, the mixing is complete and the UHPC is ready for discharge. Higher-energy shear mixers can produce UHPC in a few minutes, whereas lower-energy drum mixers could easily require 20 minutes or more to appropriately distribute the constituents and produce a fluid mixture. Care should be taken to ensure that the mixing process does not greatly increase the temperature of the UHPC, as this can