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Ultra-High-Performance Concrete: An Emerging Technology Report

Reported by ACI Committee 239

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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.

CONTENTS

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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

(a)

(b)

Fig. 3.3a—(a) Concrete truck mixing; and (b) field mixing using pan mixer.

result in a stiffer-than-desired mixture. Chilling the constituents, partially replacing mixture water with ice, or both, have proven to be viable means of reducing the temperatures of mixtures produced in higher temperature environments or in lower-energy mixers. Two example mixers that have been used for mixing UHPC are shown in Fig. 3.3a.

Once mixed, the workability of the UHPC and the consistency between mixtures is commonly verified with a flow table test as specified by ASTM C1437 and shown in Fig. 3.3b(a). While the typical consistency of UHPC is that of self-consolidating concrete, UHPC mixtures have been developed that can be cast with slopes up to 10 percent (Brühwiler and Denarié 2013). A stiffer mixture with less static workability is shown in Fig. 3.3b(b) and a more fluid mixture is shown in Fig. 3.3b(c).

(a)

(b)

(c)

Fig. 3.3b—Flow test as described in ASTM C1437.

3.4—Placement

Before placing UHPC, plan the process carefully to ensure that a UHPC with the desired quality is produced. It is important to remember that UHPC can differ greatly from conventional concrete. It can vary in consistency from that of self-consolidating concrete to that of a very low-slump mixture. Due to the potential high flowability and lack of coarse aggregate in the material, forms should be well sealed. The addition of fibers can cause the material to be very difficult to consolidate properly within the formwork. UHPC should be placed in a continuous placement without cold joints. Cold joints prevent the formation of a continuous, well-distributed fiber network across the joints. As in conventional concrete, over-vibration of UHPC can cause fiber settlement in the formwork and inadequate fiber distribution in the member. Overdosing the UHPC with water or high-range water-reducing admixtures during mixing will compound this settlement problem. Fiber alignment is also dependent on the manner of placement and how the UHPC flows in the formwork.

3.5—Curing

Many factors affect the manner and time period of curing in UHPC. As with conventional concrete, high-range water-reducing admixture dosage impacts initial set and can delay set by up to 24 to 36 hours (Morin et al. 2001), although certain cement types, chemical admixtures, or both, can offset this effect. The method of curing can also impact the resulting material properties of UHPC (Graybeal 2006b; Graybeal and Stone 2012). Some varieties of UHPC require curing regimens that specify elevated temperatures and moisture levels for specific periods of time. UHPC may be subjected to heat, pressure treatment, or both, at early ages. These treatments can increase the density by reducing the entrapped air by removing excess water and by accelerating chemical shrinkage. Post-set thermal treatment, typically 194°F (90°C), accelerates the pozzolanic reaction and modifies the microstructure of the hydrates (Richard and Cheyrezy 1995). The addition of heat serves to accelerate the hydration process. Depending on the type of thermal curing, UHPC may not gain additional strength following the completion of the curing regimen. Depending on the hardened properties desired, this type of curing may or may not be necessary. In addition, it may not be practical to provide an environment that can achieve the temperature or moisture levels required during the curing process; for example, for in-place applications.

CHAPTER 4—CONCRETE PROPERTIES

4.1—Early-age and time-dependent properties

The rate of early-age hydration of ultra-high-performance concrete (UHPC) is affected by cement type, admixtures (type and quantity), and the temperature of the material. As with conventional concrete, the rate of hydration may be faster in hot weather or with fast-setting cements and slower in cooler weather or with slower-setting cements. High dosages of admixtures containing set retarders can significantly delay initial set of UHPC (Morin et al. 2001). The rate of hydration may be accelerated by the application of heat or accelerating admixtures. When the hydration reaction begins, it is characterized by a strong release of heat and a rapid development of the mechanical properties.

Due to the high binder content in UHPC, the heat of hydration is higher than conventional concretes. Measured temperature rises in insulated cylinders are reported to range between 65 and 126°F (36 and 52°C) (Russell and Graybeal 2013; Kamen 2007; Habel 2004). As with all types of portland-cement-based concretes, UHPC undergoes early-age shrinkage (that is, bulk volume reduction). Most of this shrinkage is autogenous shrinkage (UHPC binder hydrates and chemically combines with the water within the mixture).

Table 4.2—Comparison of conventional concrete and UHPC

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

In special cases where early attainment of mechanical properties is desired, a thermal treatment may be applied to the UHPC after final set is achieved. As stated previously, typical thermal treatments, which differ from early heat for accelerating setting, can be upwards of 190°F (90°C) at 95 percent relative humidity, for approximately 48 hours. At the end of the thermal treatment process, the mechanical properties are fully attained and the UHPC is considered dimensionally stable.

UHPC is a portland-cement-based composite that experiences volume changes due to creep and shrinkage (Habel et al. 2006). The amount of creep and shrinkage is dependent on the curing regimen. Researchers have reported creep coefficients (ratio of the ultimate creep strain to the elastic strain) for UHPC from 0.31 (steam cured) to 0.8 (for non-heat-cured) (Graybeal 2006b; Wiens and Schmidt 2008). Shrinkage values are in the same order of magnitude as conventional concrete and can attain values of up to 900 $\mu\varepsilon$, dependent on the curing regimen (Kamen 2007; Graybeal 2006b). Due to a high rate of early shrinkage prior to the development of tensile resistance, caution should be taken to minimize restraint due to formwork and existing structural elements. Similar to early-age UHPC, long-term shrinkage is mostly autogenous shrinkage. Once UHPC has been cured or thermally treated, there is little to no additional shrinkage.

4.2—Mechanical properties

As with conventional concrete and high-performance concrete (HPC), UHPC does not have a unique mixture formulation and, therefore, the mechanical properties of UHPC vary. Likewise, the curing conditions and testing age affect the mechanical properties of both conventional concrete and UHPC. When compared to conventional concrete, UHPC has higher strength and a higher elastic modulus. Table 4.2 provides typical ranges for selected mechanical properties of conventional concrete and UHPC.

The stress-strain behavior of UHPC in compression is more linear than conventional concrete up to its compressive strength, and the fracture of compressive specimens is more brittle (Habel 2004).

The stress-strain responses in Fig. 4.2a, obtained from direct tensile tests on 2 in. (51 mm) square cross section prisms (Graybeal 2015), provide a comparison of the tensile behavior of strain-hardening UHPCs, a pair of fiber-reinforced concretes (FRC), and conventional plain concrete. It can be seen that UHPC has a significantly higher tensile strength and sustained tensile capacity than FRC and conventional concrete. Whereas the tensile strength of conventional concrete is usually neglected in structural design calculations, the tensile behavior of UHPC is commonly included (refer to Chapter 5).

The tensile behavior of UHPC is characterized by its high strength, but more importantly by its post-cracking ductility when compared to conventional concrete. UHPC generally contains discrete and distributed reinforcement on the microscale, with the most common reinforcement being steel fibers. The type and quantity of reinforcement can be adjusted to tailor the tensile behavior to the requirements for each application. The post-cracking tensile behavior of UHPC can either be strain-hardening (that is, the resistance continues to increase after the cracking stress is reached) or strain-softening (that is, the resistance decreases after the cracking stress is reached). Once the highest tensile resistance is reached, crack localization occurs.

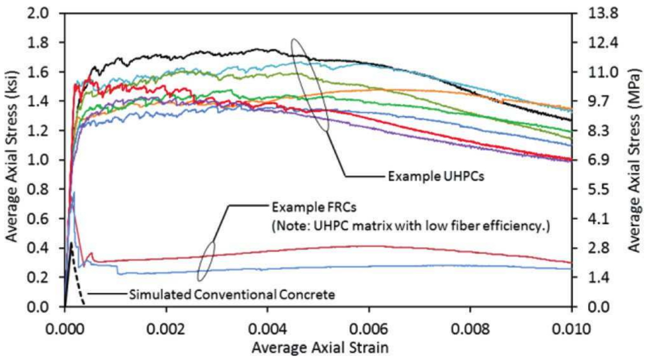


Fig. 4.2a—Example tensile behaviors of conventional concrete, FRC, and UHPC (adapted from Graybeal 2015).

Figure 4.2b shows the schematic tensile behavior of a strain-hardening UHPC in comparison to a conventional FRC. Stage I consists of linear-elastic behavior to the first cracking strength σ_{cc} (Point A). The strain hardening stage (Stage II) only occurs in the UHPC and is characterized by the formation of multiple fine cracks, and the overall behavior can be seen as a phenomenon that occurs in the entire specimen. In contrast, the stress drops in conventional FRC after the first cracking strength. Once the specimen reaches the post-cracking stress σ_{pc} (Point B), crack localization and softening occur for both the conventional FRC and the UHPC (Stage III).

The increases in tensile cracking strength and post-cracking tensile capacity, when compared to conventional concrete, also affect UHPC's impact response, toughness, and energy dissipation. UHPC's energy dissipation is 50 to 100 times greater than that of conventional concrete (Dugat et al. 1996; Parant 2003). As expected, the blast response of UHPC is better than conventional concrete (Cavill et al. 2006). Because of UHPC's impact response and energy dissipation, there is also interest in UHPC for seismic applications (Zohrevand and Mirmiran 2013; Hosinieh et al. 2015; Wille et al. 2012; Toutlemonde et al. 2016).

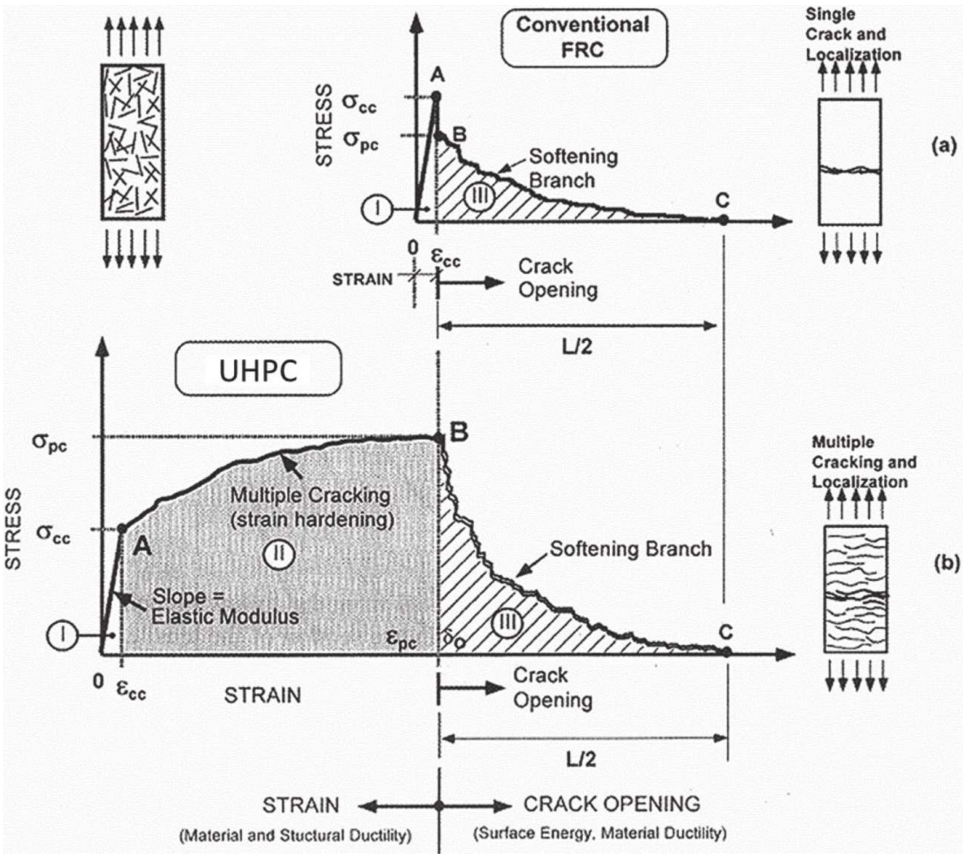


Fig. 4.2b—Schematic tensile behavior of strain-hardening UHPC and FRC (adapted from Naaman [2002]).

4.3—Durability

The durability of UHPC is superior to that of conventional concrete. This is due to the dense matrix, discontinuous microstructure, and well-dispersed microcracking of the material. UHPC demonstrates improved resistance to many kinds of harmful gases and liquids, chloride attack, frost action, and freezing-and-thawing cycles. These improvements are related to the higher density of the hydration products and of the transition zone between the matrix and the aggregates (Schmidt and Fehling 2005). The porosity of UHPC is approximately 9 percent when compared to 15 percent for conventional concrete (Roux et al. 1996). In addition, there are very few to no capillary pores in UHPC (Cheyrezy et al. 1995), which leads to a largely discontinuous pore structure. Research has shown that the water permeability coefficient is approximately one to two orders of magnitude lower than that of conventional concrete, even when the UHPC exhibits some microcracking (Roux et al. 1996; Charron et al. 2007).

The dense matrix of UHPC slows the penetration of deleterious solutions into the microstructure, and so the mechanisms that can cause conventional concrete to deteriorate are mitigated (Thomas et al. 2012). Consequently, durability properties, as measured by permeability tests, freezing-and-thawing tests, scaling tests, abrasion tests, resistance to chloride ingress, alkali-silica reaction, and carbonation are significantly better than those of conventional concrete (Russell and Graybeal 2013). UHPC has a high ohmic resistance in comparison to conventional concrete, which further reduces the corrosion risk of embedded steel reinforcing (Roux et al. 1996).

The superior performance of UHPC has been confirmed with field experiments where two different UHPC mixtures were placed at the mid-tide level of the marine exposure site at Treat Island, ME, under severe exposure conditions. Test results after exposure periods of 5 and 15 years showed no observed degradation of mechanical or durability properties and confirmed the excellent durability properties of UHPC (Thomas et al. 2012). Monitoring of UHPC beams placed in the aggressive environment of the water-cooling tower of the Cattenom nuclear power plant in France for over 10 years also demonstrates the excellent durability of UHPC (Toutlemonde et al. 2009). Similar satisfactory durability results have been obtained for Sakata Mirai pedestrian bridge and Bourg-lès-Valence road bridges (Kono et al. 2013; Toutlemonde et al. 2013).

Numerous studies have addressed fire resistance of UHPCs (Russell and Graybeal 2013). Special formulations may be developed for enhanced fire resistance. In some cases, polypropylene fibers have been shown to increase the fire resistance of this class of materials.

CHAPTER 5—STRUCTURAL DESIGN OF UHPC COMPONENTS

As previously discussed, ultra-high-performance concrete (UHPC) possesses a unique combination of increased compressive and tensile strengths, increased stiffness, sustained post-cracking tensile capacity, and extremely low porosity as compared to conventional and high-performance concretes. The advanced mechanical and durability properties of UHPC allow structural configurations that were previously not possible through the use of conventional concrete materials. Efficient engagement of these properties necessitates the use of structural design principles that extend beyond conventional methodologies.

In the near term, the use of UHPC is expected to focus on applications that use the advanced material properties of UHPC efficiently with respect to both strength and durability. The high energy dissipation capacity of UHPC can also be used for efficient design of members subjected to seismic or impact type loadings. While there is opportunity for structural members to be made entirely of UHPC, another efficient use can be through composite members with conventional concrete or other materials. Opportunities for deployment of UHPC structures will mainly be limited to applications where owners desire innovative solutions and are willing to rely on engineering expertise combined with research results until design specifications are published.

5.1—Design principles

In the design of conventional concrete, it is typically assumed that the concrete itself only carries compression and that all tensile forces are carried by discrete reinforcements such as deformed steel bars. Principles of mechanical behavior have been combined with empirical relationships to create the codified design specifications that engineers rely on today in the design of reinforced concrete structures for strength and serviceability.

The most significant potential deviation from conventional concrete design practice relates to the tensile response of UHPC as described in 4.2. If the structural members are detailed appropriately, this tensile capacity can contribute a significant proportion of the member's overall resistance to applied loadings while still affording the slender member proportions commonly associated with UHPC components. Therefore, in contrast to conventional concrete, the tensile capacity of UHPC is usually included in the design and analysis.

From a conceptual standpoint, the differences between a conventional reinforced concrete structural design specification and one relevant to the advanced properties of UHPC can be addressed through a basic understanding of mechanics of materials. One convenient means of directly considering the stress-strain response of UHPC in tension and compression is to use a strain-based design process. In a strain-based design process, the mechanical limits of the concrete can be defined in terms of both strength and strain.

For an analytical design approach, the tensile and compressive responses of the UHPC are determined; appropriate factors of safety are applied to the UHPC responses; and a simplified, conservative stress-strain relationship is obtained. This relationship is normally defined by a limited number of stress and strain parameters, as shown in Fig. 5.1a. A typical compressive stress-strain design response is shown in Fig. 5.1a(a), with linear behavior until the design compressive strength as well as a limiting strain value.

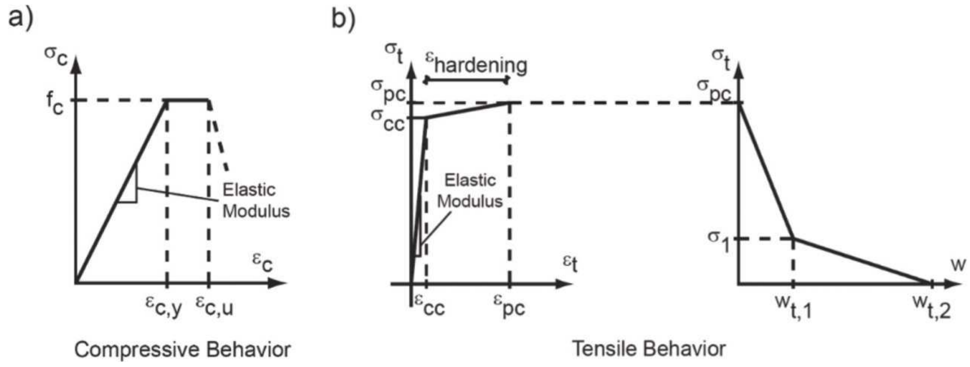


Fig. 5.1a—Example for constitutive relationships for UHPC at the ultimate limit state (ULS) in: (a) compression; and (b) strain-hardening in tension.

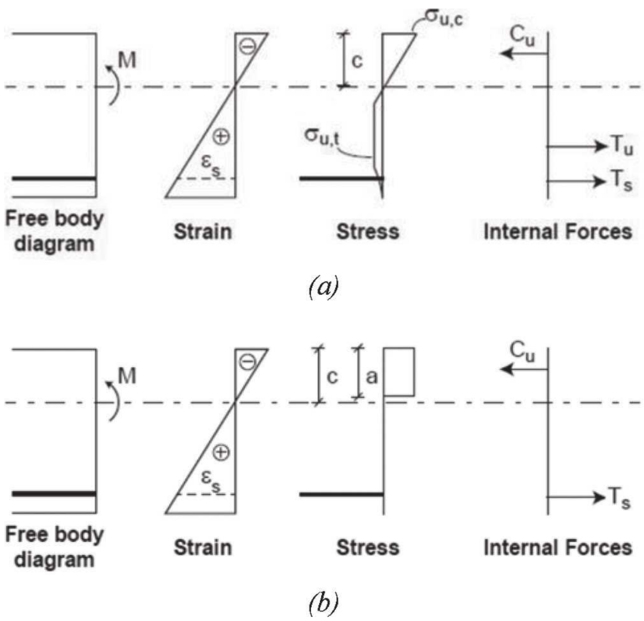


Fig. 5.1b—Bending constitutive relationships at ULS for: (a) reinforced UHPC; and (b) reinforced conventional concrete.

Example tensile design responses include a strain-softening behavior, a strain-hardening behavior (Fig. 5.1a(b)), an elastic-plastic behavior, and a rigid-plastic response at the tensile cracking strength through a limiting strain value.

As an example, Fig. 5.1b(a) provides typical strain, stress, and force diagrams for a UHPC beam in bending at its ultimate limit state (ULS), where the beam satisfies the well-known hypothesis that plane sections remain plane. For comparison, the typical design relationships for conventional concrete are given in Fig. 5.1b(b). Differences occur in both the compression and tension zones of the materials.

Addressing differences in the durability of UHPC as compared to conventional concretes can also be handled through modifications to existing design specification provisions. Structural design specifications commonly address durability considerations through provisions that specify reinforcement cover requirements and that specify reinforcement configurations to effectively limit crack widths. The reduced permeability of UHPC can facilitate a reduction in cover requirements and make efficient use of UHPC as a moisture barrier. Crack width limitations are addressed implicitly through the internal fiber reinforcement in the UHPC formulation, which provides a significant post-cracking tensile resistance.

5.2—Structural design guidance for UHPC

Structural design specification development is underway in various jurisdictions around the world. French guidelines AFGC (2002, 2013) were followed by NF P18-710, which is a formal design standard for UHPC (Toutlemonde and Delort 2016). AFGC (2013) provides a framework for the design of UHPC components subject to the most common structural loading conditions. The recommendations in this report are based on and are relevant to the types of UHPC formulations that are commonly produced and deployed in France and the United States. Of note, these guidelines include methods for handling structural design of fiber-reinforced UHPC, including local and global fiber efficiency factors, test methods for quantification of the tensile response of a UHPC formulation, and resistance factors based on structural testing of UHPC components.

Design guidance has been developed in Japan (Japanese Society of Civil Engineers 2008), Germany (Schmidt 2008), and Switzerland (Cahier Technique prSIA 2052 2014). The International Federation of Structural Concrete (*fib*) is developing guidance through Task Group 8.6 that aligns with the 2010 Model Code and more broadly the Eurocode (Walraven 2012).

5.3—Structural research needs

Because the immediate practical relevance of a UHPC structural application commonly drives the research being completed and the behavioral relationships being developed, some jurisdictions have focused on the development of component-specific design guidance. In the United States, the Federal Highway Administration has published guidance for the design and construction of field-cast UHPC connections between prefabricated structural components (Graybeal 2014). Researchers have also produced a guideline for the design of two-way ribbed precast UHPC bridge deck systems (Aaleti et al. 2013). In Australia, a guideline for the design of prestressed UHPC beams has also been published (Gowripalan and Gilbert 2000).

CHAPTER 6—APPLICATIONS

Ultra-high-performance concrete (UHPC) has been employed in a variety of applications ranging from pedestrian bridges to architectural facades. In this chapter, selected examples of the use of UHPC are discussed. Many more examples exist within and beyond these categories.

6.1—Highway bridges

The advanced properties of UHPC facilitate the development of novel bridge superstructures whose longer spans, shallower depths, and enhanced durability provide new opportunities for the bridge sector. The tensile response of UHPC can allow for the reduction of primary reinforcements and the elimination of secondary reinforcements, thus reducing fabrication costs and mitigating long-term corrosion degradation issues. The high ultimate compressive stress can allow for increased prestressing levels and, thus, more efficient structures.

The U.S. Federal Highway Administration has led an effort through its UHPC research program to develop a family of UHPC prestressed bridge girders for single-span bridges spanning up to 135 ft (40 m). The elements of the research program are shown in Fig. 6.1. The pi-girder is a bulb-double-tee shape with an integral deck and a high span-depth ratio. Computational modeling, full-scale fabrication, structural performance testing, and an initial field deployment have been completed. The pi-girder resists shear forces through the UHPC in the webs, thus eliminating the need for conventional shear reinforcement and the associated concrete cover. The 4 in. (100 mm) thick pi-girder deck is capable of distributing loads well in excess of the design wheel loads in bridge design specifications. The bridge system includes longitudinal deck-level connections between elements and transverse diaphragms connecting the bulbs (Graybeal 2009a,b; Keierleber et al. 2010; Chen and Graybeal 2010, 2012; Zhang et al. 2013).

6.2—Pedestrian bridges

The first UHPC pedestrian/bikeway bridge (Fig. 6.2a) was built in Sherbrooke, QC, Canada in 1997. The bridge is an open-web space truss and spans 197 ft (60 m) across the Magog River in downtown Sherbrooke. The top and bottom chords of the bridge were cast with a concrete that had a compressive strength of 29,000 psi (200 MPa). The bridge deck is 1.2 in. (30 mm) thick and is 130 in. (3.3 m) wide (Blaise and Couture 1999). Another example of a UHPC pedestrian bridge is the Sakata-Mirai Bridge in Sakata, Japan (Fig. 6.2b). The bridge spans 165 ft (50.2 m) and consists of six precast segments. The bridge's self-weight is approximately 80 percent less than a similar bridge cast with conventional concrete. The reduction in self-weight resulted in a cost reduction of 10 percent (Rebentrost and Cavill 2006).

Other examples of pedestrian bridges are the extremely slender U-shaped footbridge to the MuCEM in Marseille, France (Fig. 6.2c) (Mazzacane et al. 2013), and the U-shaped truss bridge over the Oveja's ravine in Alicante, Spain (Fig. 6.2d) (Lopez et al. 2014).

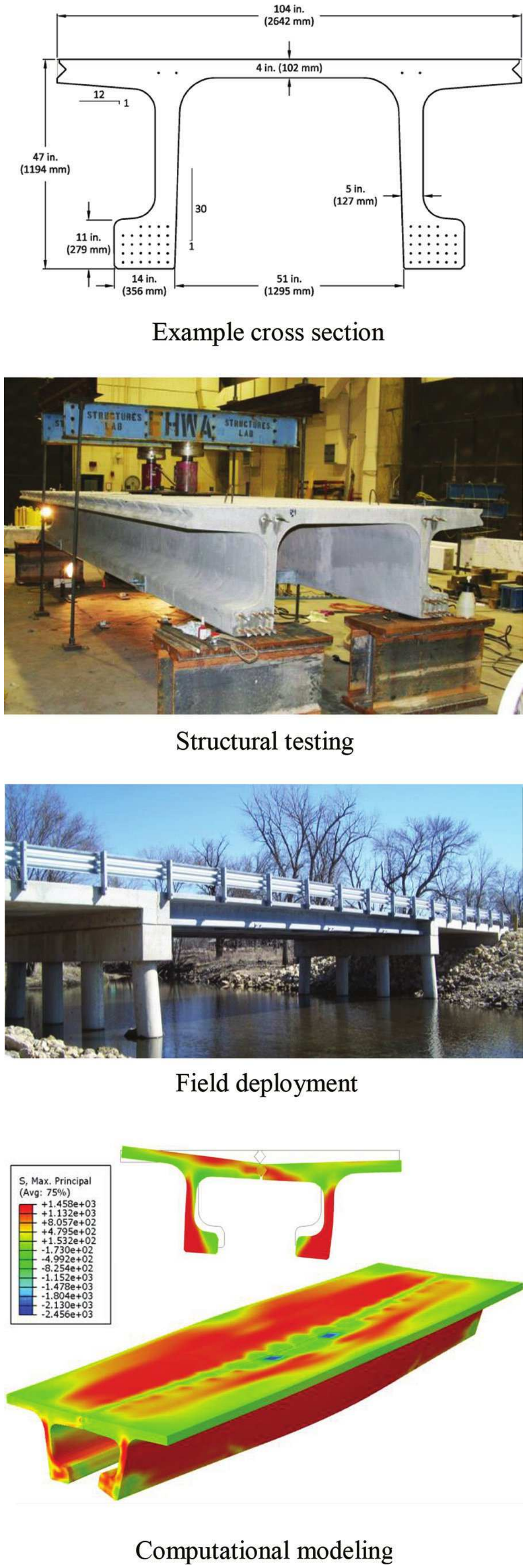


Fig. 6.1—FHWA research on UHPC highway bridges.

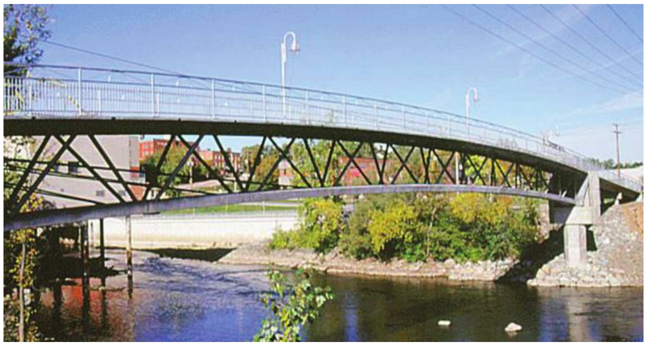


Fig. 6.2a—Sherbrooke Pedestrian Bridge (photo courtesy of Lafarge).

Fig. 6.2b—Sakata-Mirai Bridge (photo courtesy of Lafarge).

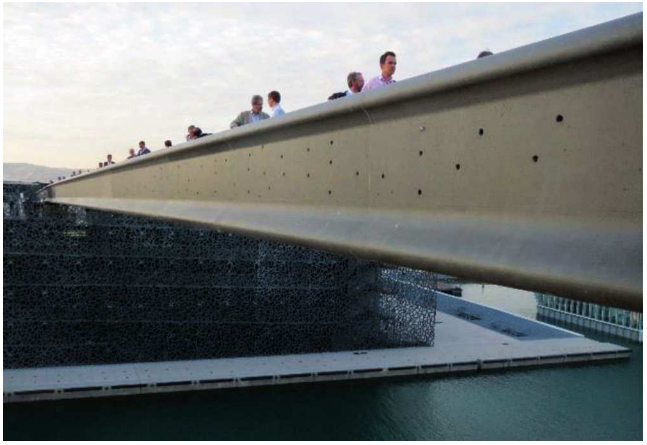


Fig. 6.2c—MuCEM Pedestrian Bridge, Marseille, France (photo courtesy of Ben Graybeal).

6.3—Seismic retrofit

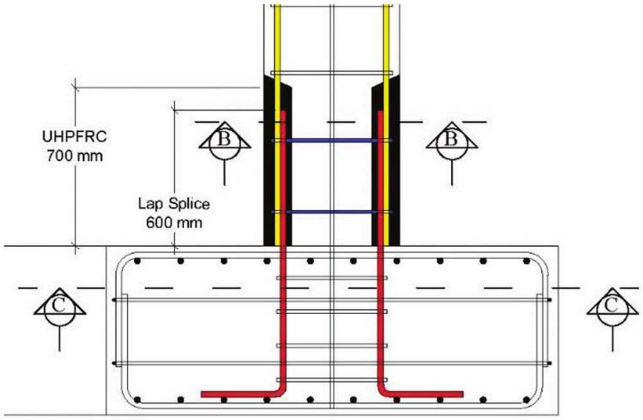
Recent research has shown that UHPC can also be used for seismic retrofit of columns. Massicotte et al. (2013) proposed UHPC to retrofit insufficient reinforcing bar splices typically found in older bridge pier columns (Fig. 6.3(a)). The aim of this retrofit is to replace existing concrete with UHPC, reduce reinforcing bar splice length, and eliminate spalling and longitudinal bar buckling. In another seismic application, UHPC combined with steel reinforcing bars was used in two column jackets to improve drift capacity of an existing concrete pier to accommodate liquefaction displacements at the Mission Bridge, Mission, BC, Canada (Fig. 6.3(b) and 6.3(c)). The jackets were a simple solution to more traditional steel or concrete elliptical jackets, which are costly for large rectangular columns (Kennedy et al. 2015).

Fig. 6.2d—Pedestrian Bridge over Oveja's ravine, Alicante, Spain (photo courtesy of B. Massicotte).

6.4—Rehabilitation

UHPC has been used in the rehabilitation of structures. Examples include thin unreinforced and reinforced watertight protection layers and reinforced structural layers on bridge decks (Fig. 6.4(a) and (b)). The density of the UHPC allows elimination of separate waterproofing. UHPC is often used to fulfill the dual purpose of enhancing mechanical performance and durability of the structure. Strengthening of slabs typically consists of increases in flexural capacity, particularly in negative moment regions, an increase in punching shear capacity, or both. It can be achieved using UHPC with and without added reinforcing bars. Studies and field applications have shown that debonding between existing concrete and UHPC is typically not a concern when appropriate surface preparation methods are used. The UHPC used in these overlay applications is typically self-consolidating, but can accommodate a slope of up to 10 percent on the free top deck surface (Brühwiler and Denarié 2013). Typical layer thickness for unreinforced UHPC layers is approximately 1.25 in. (30 mm), and 2 in. (50 mm) for reinforced layers. The UHPC layer can either accommodate a 2 in. (50 mm) thick asphalt layer or it can have gravel pressed into the surface to obtain a skid-resistant wearing surface.

The first UHPC overlay was constructed in 1992 in Taiwan. Another was constructed in Switzerland in 2004 (Fig. 6.4(a)) and has been regularly monitored since. The UHPC overlay in Switzerland continues to be in good condition and shows no signs of deterioration. Figure 6.4(b) shows a large-scale UHPC deck overlay for strengthening and increasing durability on the Chillon Viaducts in Switzerland in 2014 (Brühwiler et al. 2015). More than 3200 yd^3 (2400 m^3) of UHPC



(a)

(b)

(c)

Fig. 6.3—(a) Seismic reinforcing bar splice retrofit (Massicotte et al. 2013); (b) casting of Mission Bridge UHPC jacket (Kennedy et al. 2015); and (c) final Mission Bridge UHPC jackets (Kennedy et al. 2015).

were mixed in a mobile plant on site and placed in an automated process over more than 540,000 ft^2 (50,000 m^2) of deck area. UHPC has also been applied as protective layers to vertical elements such as roadside barriers and bridge piers (Fig. 6.4(c)) in Switzerland and Canada (Doiron and Perry 2014).

(a)

(b)

(c)

Fig. 6.4—(a) UHPC bridge deck rehabilitation in Switzerland (Brühwiler and Denarié 2013); (b) large-scale structural UHPC deck overlay, Viaduc de Chillon, Switzerland (Brühwiler et al. 2015); and (c) pier repair in Canada (Doiron and Perry 2014).

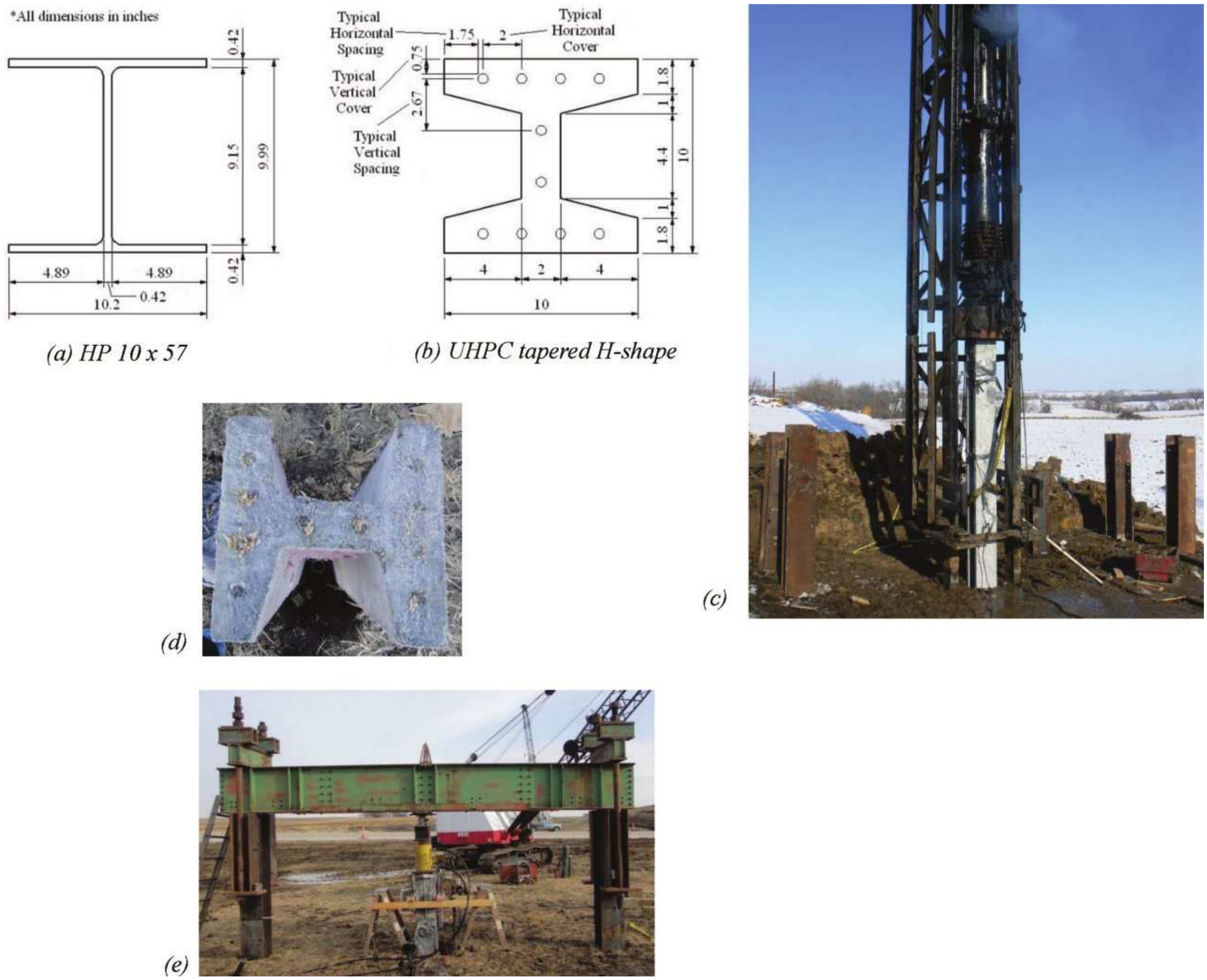


Fig. 6.5—Implementation of UHPC in prestressed precast pile foundations: (a) cross section details; (b) field splicing; (c) pile driving; (d) condition of H-pile after driving; and (e) field testing of UHPC pile (Vande Voort et al. 2008; Aaleti et al. 2012).

6.5—Piles/foundations

Steel H-piles and precast, prestressed concrete piles are most commonly used in bridge foundations to transfer the vehicular load to the soil. Minimizing bridge foundation deterioration is a primary challenge that significantly increases bridge service life and reduces life-cycle maintenance costs. Traditional piles composed of steel and concrete are subjected to corrosion and deterioration. During the pile-driving process, steel piles are susceptible to local buckling, whereas prestressed concrete piles are susceptible to cracking due to high tensile and compressive stresses.

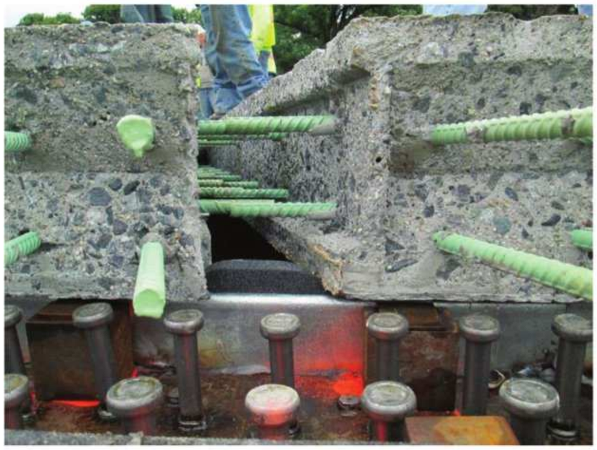
Taking advantage of the durability and mechanical properties (high compressive and sustainable tensile strengths) of UHPC, an optimized, prestressed H-pile was developed (Vande Voort et al. 2008). The optimized H-pile section (refer to Fig. 6.5(a)) consists of ten 0.5 in. (12.7 mm) diameter prestressing strands and has the same outer dimensions, moment capacity, and mass as the standard HP 10 x 57 steel piles. An extensive research study involving laboratory and field testing (Fig. 6.5(e)) was done to characterize the section behavior under different soil and driving conditions and to develop connection details (Fig. 6.5(b)) for field implementation (Aaleti et al. 2012). This study found that the UHPC pile did not experience any damage during driving (Fig. 6.5(d)) and had 86 percent higher axial load capacity compared to a standard HP 10 x 57 piles; thus, fewer piles could be used for a given application. Following this study, the first UHPC H-pile in the United States was implemented in a 223 ft (68 m) long integral abutment bridge in Sac County, Iowa. The pile was 55 ft (16.8 m) long and was driven in a clay soil site as a replacement for a standard steel pile (Garder 2012).

6.6—Field-cast connections

The use of prefabricated components in infrastructure construction is commonplace; however, the deployment of this type of construction process places unique demands on the connections between the elements. These connections should facilitate construction and provide appropriate resistance to structural and environmental loads, and should not significantly increase the cost of the overall structure.

Bridge with UHPC connections

Composite connection detail



Deck-level connection detail

Field casting of UHPC

Fig. 6.6—Field-cast UHPC connections.

Connection details used to connect concrete components in the past have sometimes exhibited poor performance while not offering significant construction advantages.

The advanced properties of UHPC allow for the redesign of connection details to create robust systems that are easier to construct and emulate or exceed the performance of monolithic systems. In this application, UHPC can be viewed as a field-cast grout whose properties allow for shortened development length of embedded reinforcements, increased bond strength to mating surfaces, and enhanced durability as compared to commonly deployed grouts. Physical testing under static and cyclic loads has demonstrated that mild steel deformed reinforcing bars can be developed within approximately eight times the bar diameter, thus allowing for the lap splicing of straight bars within comparatively narrow connections (Graybeal 2014). Shear connections that allow for a reduction or elimination of the interlacement of reinforcements emanating from mating components have also been developed and tested.

Field-cast UHPC connections are beginning to be used in highway bridges around the United States and Canada (Fig. 6.6). Over 130 bridges have been constructed with this connection technology through 2015 in the United States and Canada (Federal Highway Administration 2016). The New York State Department of Transportation and the Ontario Ministry of Transportation have been lead agencies in the adoption of this technology. Connection types used include longitudinal and transverse deck-level connections, deck-to-girder connections, decked-girder connections, adjacent box beam connections, link slab connections, barrier rail connections, and prefabricated substructure connections.

Fig. 6.7a—Back side of UHPC panel (Cavill et al. 2006).

Fig. 6.7b—Back side of 7252 psi (50 MPa) concrete panel (Cavill et al. 2006).

6.7—Safety and security

As with most UHPC applications, the higher strengths, increased ductility, and post-cracking tensile strength make it an attractive option and solution for structures requiring resistance to blast and projectile loadings. The high-fibered matrix allows for bridging of microcracks and post-cracking elasto-plastic behavior, which distribute strains across a larger area of the panel. Concrete security panels cast with UHPC can be thinner but perform better than panels cast with conventional concrete. Through blast loadings, fragment impact simulations, close charge tests, and ballistic tests, the blast response and impact resistance of UHPC panels were examined (Cavill et al. 2006). Two of the panels are shown in Fig. 6.7a and 6.7b. Both panels were located equal distances from the same explosive load. As seen in the figures, the damage in the UHPC panel was less than that in the conventional concrete panel. When compared with conventional concrete panels, UHPC panels can be thinner and injury caused by concrete fragments almost eliminated (Cavill et al. 2006).

An example of the use of UHPC for high security installation is shown in Fig. 6.7c. The 4 in. (100 mm) thick panels

Fig. 6.7c—UHPC roof security panels ready for delivery and after installation (Cavill et al. 2006).

were installed to provide increased security against weapons effects on the roof of the structure.

6.8—Spent nuclear fuel storage

The nuclear power industry depends heavily on the use of dry storage casks to store spent nuclear fuel rods following their removal from a wet storage pool inside the reactor containment vessel. The casks are of several designs, but normally have thick stainless steel outer and inner walls with the gap filled with concrete. The concrete serves a structural function to protect the spent fuel rods from natural and manmade disasters and a protective function to shield those outside the cask from nuclear radiation. Once loaded with spent fuel rods, the casks are welded shut and positioned on an engineered concrete slab for long-term storage. In their current form, the casks use conventional concrete produced with a high-density aggregate to improve radiation shielding abilities. The long-term durability of the casks is not known; thus, the Nuclear Regulatory Commission only certifies them for 20 years before recertification is required (United States Nuclear Regulatory Commission 1997).

While there are no ultra-high-performance concrete (UHPC) casks currently in use, this is a potential future use of the material that deserves further study. The application of UHPC in dry storage casks could result in a reduction in the diameter and mass of the dry storage casks, allowing the placement of more casks on the same storage pad. In addition, based on the improved durability and strength characteristics of UHPC in comparison to conventional concrete, it is anticipated that certification for longer than 20 years would be possible. Preliminary studies of UHPC containers with respect to mechanical shock resistance were performed by Sercombe et al. (1998).

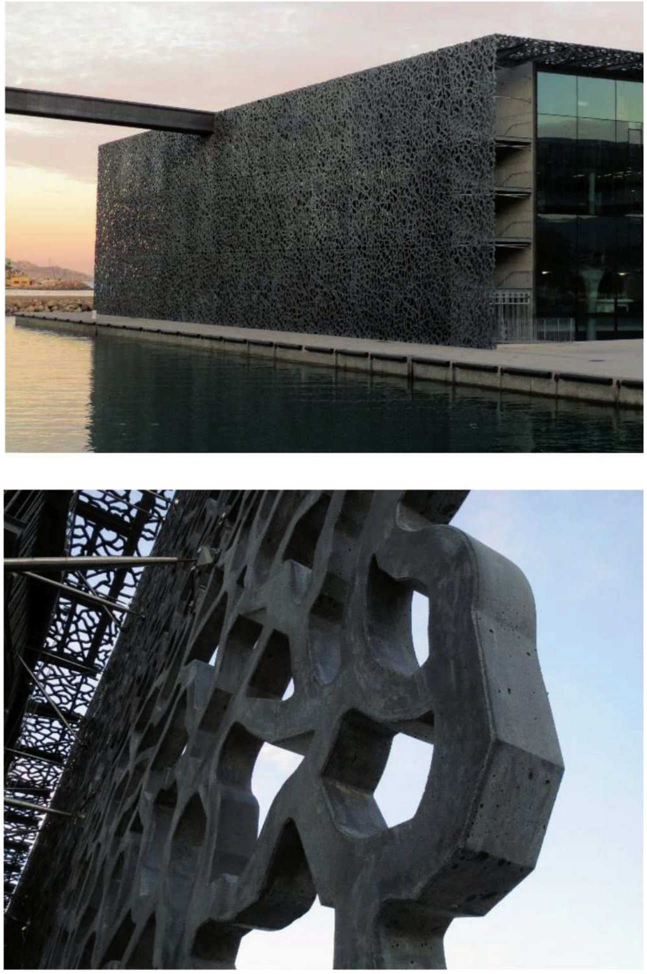


Fig. 6.9—MuCEM general overview and close-up of facade panels (photos courtesy of Ben Graybeal).

6.9—Facades

Building facades are becoming an important application of ultra-high-performance concrete (UHPC). It is used for second-skins, solar shadings, latticework, and opaque mineral panels. For facades, the use of UHPC has many advantages. It provides high durability for those exposed elements and allows very complex forms to be produced with tight construction tolerances. The quality of the finished surface is also an important architectural criterion. The Museum for European and Mediterranean Civilizations (MuCEM) in Marseille, France, is an example of UHPC applications (Fig. 6.9) (Mazzacane et al. 2013). The building is inside an UHPC lace; openwork panels allow light and air inside while breaking the wind. Three hundred and eighty-four net facade panels were cast with UHPC to cover two sides of the museum and its roof. The panels are 19.7 x 9.8 ft (6 x 3 m) and the full/empty ratio is approximately 50 percent.

6.10—Impact resistance

One unique application for ultra-high-performance concrete (UHPC) recently studied by the U.S. Army Corps of Engineers is retrofitting critical locations in inland navigation structures (for example, locks and dams) (Green et al. 2014). One critical location studied is wall armoring systems on lock walls, approach walls, and barrier walls that are frequently impacted by vessels. The presence and adequate performance of these wall-armoring systems is important to mitigate damage to critical components in the lock (miter gates) and to ensure safety to users of the lock (prevent damaged concrete or bent steel from encroaching into the lock chamber). Figure 6.10a depicts a damaged armor component near a miter gate recess in an inland navigation structure.

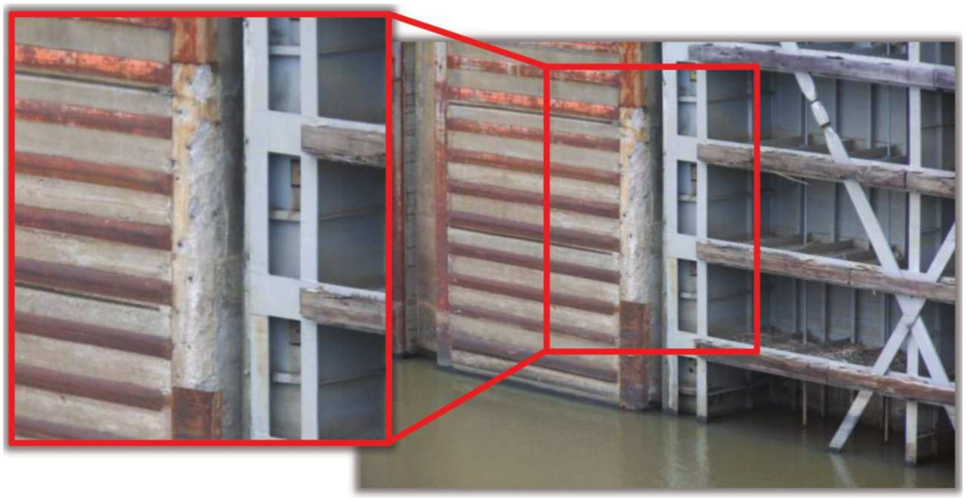
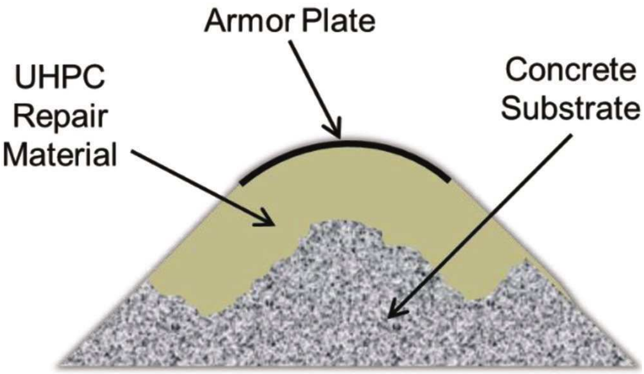


Fig. 6.10a—Typical damage vertical armor plate component at miter gate recess in inland navigation lock structure (photo courtesy of Robert Moser).

(a) Placement of repair material by pouring through ports (photo courtesy of Robert Moster)



(b) Configuration of UHPC repair

Fig. 6.10b—Placement of UHPC repair material in cavity behind armor plate.

A small-scale field demonstration project was constructed at Newt Graham Lock and Dam near Tulsa, OK (Green et al. 2014). A fiber-reinforced prepackaged UHPC was mixed on-site using a twin paddle mixer. Following mixing, the UHPC was placed into the cavity behind the armor plate by pouring through ports in the surface of the armor plate. External vibration was applied to consolidate the material after placement. Figure 6.10b shows examples of the placement and the UHPC material as seen from the exposed top of the armor plating. No heat treatment was applied to the UHPC following placement. Given the limited access to a heat or steam source for typical UHPC curing, ambient curing was performed with temperatures ranging from 60 to 70°F (15 to 21°C). This project was successfully completed in 2013.

6.11—Aggressive environments

Ultra-high-performance concrete's (UHPC) low permeability and high abrasion resistance makes it suitable for corrosive and harsh environments such as underground utilities, marine structures, hydro-electric dams, and products for wastewater treatment plants. Its strength, ductility, and

Fig. 6.11a—UHPC troughs for the Gold Bar Wastewater Treatment Plant, Edmonton, AB, Canada (McCraven 2007).

durability properties allow it to compete against materials such as stainless steel for wastewater treatment plant troughs (Fig. 6.11a). At the Gold Bar Wastewater Treatment Plant in Edmonton, AB, Canada, 3280 ft (1000 m) of UHPC troughs were installed (McCraven 2007). The 2 x 2 ft (0.6 x 0.6 m) troughs have a wall thickness of 0.7 in. (17.5 mm) and are 15 ft (4.6 m) long.

The City of Naperville, IL, began to use UHPC at the end of 2006 to repair deteriorated manhole access shafts, which constitute a very aggressive environment. The city trained and used its own crew to mix and install the product, which was sprayed using a rotating nozzle head (Fig. 6.11b).

An example of the use of UHPC restoring a dam spillway subjected to high abrasion and cavitations in a saturated condition is the Caderousse Dam (Fig. 6.11c) (Guingot et al. 2009). The UHPC was batched and mixed in concrete trucks, then pumped over 460 ft (140 m) to the repair surface area of 880 ft^2 (82 m^2).

Due to their low mass and high corrosion resistance, UHPC precast prestressed girders were selected and installed in Cattenom nuclear cooling tower between 1996 and 1998 to support mechanical equipment for an upgrade to the plant (Fig. 6.11d). The beams are located in the cooling water flow

Fig. 6.11b—Rotating spray nozzle and finished sprayed surface (photos courtesy of City of Naperville).

Fig. 6.11c—Placing UHPC in Caderousse Dam Spillway by pump (photo courtesy of Lafarge).

and are subjected to heating and cooling cycles, abrasion and corrosive waters containing chlorine, and sulfates (Toutlemonde et al. 2009). Following 10 years of exposure, cores were taken from the beams during a maintenance shut down. Analysis of these cores confirmed the absence of corrosion within the beams.

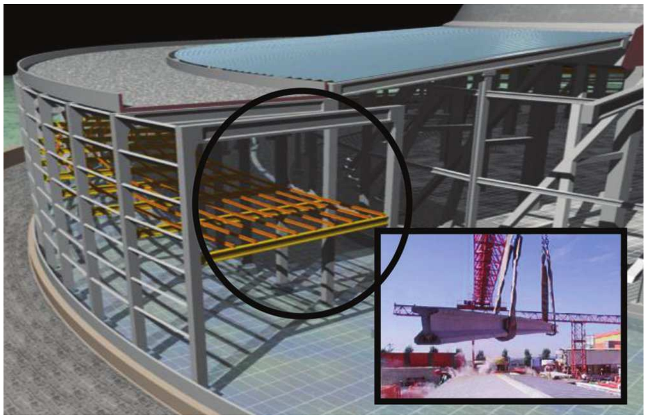


Fig. 6.11d—UHPC beams for Cattenom Nuclear Cooling Tower (Toutlemonde et al. 2009).

Fig. 6.12a—The Shawnessy Light Rail Transit (LRT) Station (photo courtesy of Lafarge).

6.12—Canopies/shells

The first use of ultra-high-performance concrete (UHPC) for a thin-shelled canopy roof was in Calgary, AB, Canada in 2004 (Fig. 6.12a). This very thin, 3/4 in. (20 mm), architectural and structural shell consists of 24 double curved thin-shelled precast concrete canopies measuring 16 x 20 ft (5 x 6 m) in plan, each supported by three struts on single columns all manufactured with UHPC (Vincenzino et al. 2005). Due to the low permeability of the UHPC, the shells provide a watertight surface and there is no waterproofing membrane applied to the structure, permitting the aesthetics of the smooth white surface to be visible.

The tollgate roof of the Millau Viaduct in France was designed as a twisted horizontal concrete wall, 320 ft (98 m) long and 92 ft (28 m) wide, with a 2-degree angle (Fig. 6.12b). UHPC allowed the use of thin membranes and light and complex shapes. UHPC also afforded high durability and tight construction tolerances necessary for this project. The roof is composed of 53 prefabricated segments connected by horizontal prestressing. The shell thickness varies between 8 and 22 in. (200 and 850 mm) and is composed of two 4 in. (100 mm) concrete skins and an expanded polystyrene (EPS) foam core. UHPC containing steel fibers was used, which eliminated the need for any passive steel reinforcement (Hajar et al. 2004; Krummenacher 2007).

Fig. 6.12b—General overview of Millau Viaduct toll gate roof.

CHAPTER 7—CONCLUSIONS

Ultra-high-performance concrete (UHPC) is an advanced cementitious material with greater strength, tensile ductility, and durability properties when compared with conventional and high-performance concrete. Because of these improved properties, opportunities and applications that were not possible with conventional concrete are now possible with UHPC. As with any emerging technology, UHPC must find its niche within the world construction marketplace. Over the coming years, increased experience among professionals, improved design guidance, standardization, and broader material availability will facilitate the increase of UHPC usage. This report serves to educate the profession on this class of materials and make project owners, designers, and contractors aware of what UHPC has done and inspire them to use it for new and varied applications in the future.

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