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Suggested Updates for the Inclusion of Guidance on Ultra-High Performance Concrete to USACE Engineering Manual 1110-2-2000, *Standard Practice for Concrete for Civil Works Structures*

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Abstract

Ultra-high performance concrete (UHPC) is a relatively modern class of concrete with properties that include very high compressive strengths, increased tensile strengths, very low permeability, and superior durability compared to conventional, normal-strength concrete. As research of this material continues to progress, its applications under both military and civil works categories expand. However, mixture and structural design guidance using UHPC is limited, particularly in the United States. This special report provides an overview of UHPC as initial guidance for the US Army Corps of Engineers (USACE) so that the material may be more easily utilized in civil works infrastructure. The information contained in this report is based on years of experience researching and developing UHPC at the US Army Engineer Research and Development Center (ERDC) and is intended to be a basis for the incorporation of this material class into USACE Engineer Manual (EM) 1110-2-2000, *Standard Practice for Concrete for Civil Works Structures,* when it is next updated.

Contents

Preface

This study was conducted for the US Army Corps of Engineers Navigation Systems Program under Project 493064, "UHPC Panels." The technical monitor was Dr. Stephanie G. Wood.

The work was performed by the Concrete and Materials Branch (GM-C) of the Engineering Systems and Materials Division (ESMD), US Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Dr. Jameson D. Shannon was chief, GM-C; Mr. Justin S. Strickler was chief, GM; and Mr. Charles E. Wiggins was the technical director for navigation. The deputy director of ERDC-GSL was Mr. Charles W. Ertle II, and the director was Mr. Bartley P. Durst.

COL Christian Patterson was the commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

The US Army Corps of Engineers (USACE) Engineer Manuals (EMs) are official public documents originating from Headquarters USACE and are advocated by USACE Directorates. They are used to provide technical guidance and procedures for various activities and aspects of construction for which the USACE is responsible. EM 1110-2-2000, *Standard Practice for Concrete for Civil Works Structures,* provides “information and guidance for the investigation and selection of concrete materials for civil works concrete structures.” The current edition of this manual was published in February 1994 with subsequent updates in July 1994 and March 2001. Since then, drastic changes in concrete materials and concrete technologies have been developed with no updates to the EM reflecting these advancements.

1.2 Purpose

This special report outlines proposed updates for the inclusion of ultra-high performance concrete (UHPC) guidance into EM 1110-2-2000 under “Special Concretes” in Chapter 10. These suggested updates are based on many years of experience evaluating and developing UHPCs at the US Army Engineer Research and Development Center (ERDC), formerly Waterways Experiment Station (WES), for the USACE and military engineering applications. This document is a product of a project under the Navigation Systems Research Program (NavSys) entitled “Development of Ultra-High Performance Concrete Panels for Navigation Lock Wall Repair.” The project consisted of the development of a nonproprietary UHPC mixture and small- and large-scale testing to evaluate the performance of that mixture compared to conventional concrete and a proprietary UHPC called Ductal J1000. Historical knowledge combined with results obtained in the recent NavSys project serve as the basis for new guidance on the development and applications of UHPC for the USACE. The section headings in this report are suggested headings for subsections within the EM.

2 General

Ultra-high performance concrete is a relatively modern class of concrete that began development in the late 1980s. It became commercially available in its current form in the United States circa 2000. Initial applications were limited and primarily included bridge elements and connections. With the proliferation of knowledge of this material class and concrete constituent technologies related to chemical admixtures, supplementary cementitious materials (SCMs), and fiber reinforcement, the range of applications for UHPC has broadened under both military and civil works categories.

Typical characteristics for this class of concrete include the following: high compressive strength; appreciable tensile strength; high density; decreased permeability and porosity; low water-to-cementitious materials ratio (w/cm); high volumes of SCMs, particularly silica fume; reduction of nominal maximum size aggregate (NMSA), which often means complete removal of coarse aggregates; high chemical admixture dosages; fiber reinforcement; and self-leveling or self-consolidating capabilities.

3 Definition

As with most concretes, compressive strength is the typical earmark for classification. The prevailing definition for UHPC is concrete with a compressive strength above 21.7 ksi (150 MPa)[*]. This is the definition provided by the French (SETRA-AFGC 2002) and Japanese (Japanese Society of Civil Engineers 2008) standards, the Federal Highway Administration (FHWA), and American Concrete Institute (ACI) Committee 239 (2018), with each one having slightly different additional criteria based on properties such as tensile capacity (i.e., tensile strength) of at least 0.72 ksi (5 MPa), discontinuous porosity, fiber reinforcement, and/or durability. Other organizations have slightly lower minimums for UHPC compressive strength, with the USACE (1994) using 20 ksi (138 MPa) and the Portland Cement Association (PCA) using 17 ksi (117 MPa). Both organizations also have additional criteria for a concrete to be classified as a UHPC. Although compressive strength is the primary property used to define UHPC, it is generally less important than other properties when attempting to predict or stipulate performance. Other important properties include tensile strength, tensile strain capacity, toughness, permeability, abrasion resistance, postyield load-carrying capacity, bond strength, rebar pullout strength, stiffness, dynamic response to blast or impact, and durability, and they should be tailored to the specific application for true material optimization.

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[*] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

4 Materials

Although the constituents of UHPC mixtures vary depending on the application, they typically include portland cement, high volumes of silica fume, fine sand, fibers, high-range water-reducing admixtures (HRWRAs), and low amounts of water. Because the mixture proportioning of UHPC mixtures is based on optimum particle packing density, mixtures may also include fly ash, limestone or quartz flour, and other SCMs and fine powders. Coarse aggregate fractions are often, but not always, eliminated entirely.

Material selection is of utmost importance in UHPC production. Any deviation from the specific materials used in the mixture proportioning phase for a UHPC can result in a drastic performance change. Therefore, not only must high-quality materials be selected, but a thorough analysis of that specific constituent's supply chain must be considered before a UHPC can be brought to production. Items to be considered include cement characteristics, aggregate size, strength, shape, texture, supplementary cementitious material characteristics, particle sizes, fiber reinforcement, and chemical admixtures. Trial mixtures are essential to ensure that required concrete properties will be obtained.

4.1 Portland cement properties

As with high-strength concrete, the selection of portland cement is important. UHPCs contain very high cement contents that can result in high heat evolution as the cement hydrates, and the cement type, chemistry, and particle fineness are selected to reduce this effect. Finely ground cements react more rapidly and cause higher exothermic temperatures, so coarser-ground cements are preferred. Coarsely ground oil-well cements meeting American Petroleum Institute (API 1997) standards are modified portland cements that are tailored to withstand high temperatures and high pressures and are commonly used to produce UHPCs.

American Society for Testing and Materials (ASTM) C150 (2007) Types I, II, and V cements can be used, but these cement types have wide ranges of acceptable limits for physical and chemical requirements, thus performance can vary considerably. ASTM C150 Type III cements are typically the finest of the portland cements and are often avoided; however, they can be used in combination with appropriate SCMs. Chemically, UHPCs made with cements that have higher long-term strength gain potential and lower heat of hydration perform better. This means that cements higher in dicalcium silicate (C_2S) and lower in tricalcium aluminate (C_3A) are ideal. API oil-well cements are a great example of cement with high amounts of C_2S and low amounts of C_3A. ASTM Type III cements are the least ideal with relatively high amounts of C_3A that provide higher early strengths.

4.2 Supplementary cementitious materials (SCMs)

SCMs are generally used in high volumes in UHPC to reduce the required amount of portland cement. These high SCM volumes aid in improving strength and durability while also making the material more economical and environmentally friendly. The most common SCM for UHPC is silica fume, but other materials like fly ash, slag cement, and metakaolin are commonly used as well. Silica fume is used in high amounts, ranging from 10 to 40 percent by mass of cement. Slag cement and fly ash are used in amounts that are typical for most other concrete types. The volume increase in cementitious materials resulting from the addition of high amounts of SCMs limits the amount of concrete that can be made in a specific mixer. The water demand of the concrete mixture is dependent upon the SCMs used. Silica fume, especially at high portland cement replacement levels, increases water demand and requires the use of high dosages of HRWRAs.

4.3 Cementitious materials content

Portland cement contents are very high for UHPCs and can range from 800 to 1,400 lb/yd^3. Cementitious materials contents, the total content of portland cement and SCMs, are also very high for UHPCs when compared to other concrete types. Cementitious materials contents typically range from 1,000 to 2,000 lb/yd^3. It is common for the cementitious materials content of UHPC to almost equal or even exceed the aggregate content in terms of mass per given volume. However, as with high-strength concretes, higher strengths do not always accompany higher cementitious materials contents. The concrete strength for any given cementitious materials content will vary with the water demand of the mixture, the fluidity affecting material consolidation, and the strength-producing characteristics of the cement being used. The optimum cement/cementitious materials content will depend on the combinations of all materials being used and is best determined by trial batches. The high cementitious materials contents increase material costs; thus, considerations of performance versus economy should be made.

4.4 Aggregates

At very high compressive strengths, aggregate flaws are often the sites for crack nucleation, leading to fracture propagation and specimen failure. Generally, larger aggregates have a greater chance of containing flaws that lead to crack nucleation as the compressive stress rises above the threshold from high-strength concrete and into the UHPC range. Therefore, it is common practice to minimize the NMSA to less than 3/8 in., with most UHPC mixtures containing no coarse aggregate at all. UHPC typically contains only fine aggregates and is more similar to a sanded grout than it is to concrete. Coarse aggregates that have high hardness or heavyweight aggregates have been used successfully using larger NMSA, but these mixtures are not common.

The ideal fine aggregate or sand should be clean, well-graded, and have minimal amounts of ultra-fine particles. Due to the high cementitious materials content, coarser sands with a high fineness modulus (about 3.0) typically give better flowability and strength. Finer sands with a lower fineness modulus (below 2.5) usually increase water demand and mixture viscosity, making placement difficult. Generally, natural fine aggregates are preferred because they require less mixing water and improve workability compared to manufactured aggregates that may contain crusher fines.

In addition, it is common to choose an aggregate based on gradation to comply with various particle packing theories that optimize matrix density. These particle packing theories often lead to the use of well-graded, inert fillers such as milled silica sand, known as silica flour, to occupy a length-scale within the matrix that is not filled by other materials.

4.5 Fiber reinforcement

Two families of discontinuous fiber reinforcement are generally used—steel and polymeric. Both steel and polymeric fibers increase UHPC toughness and come in a variety of shapes, sizes, and strengths. Steel fibers increase concrete density and provide higher peak tensile strengths while polymeric fibers typically provide better tensile strain capacities. Inclusion of fibers reduces concrete flowability, and typical dosages range from 1 to 4 percent by total mixture volume, depending on the application. In general, smaller fibers tend to inhibit crack propagation better, resulting in higher peak tensile strengths, while larger fibers are better at bridging cracks in concrete, resulting in higher toughness. Increased HRWRA dosages may be required at higher fiber volume fractions. When using UHPC with traditional reinforcement, the fiber length should be considered. Bar spacings should be at least three times the fiber length, and cover depths should be at least two times the fiber length. The cost of the fibers used in UHPC is usually equal to the cost of all other materials in the mixture combined. Thus, careful consideration should be made for performance versus economy.

4.6 High-range water-reducing admixture (HRWRA)

HRWRAs are necessary in the production of UHPC. At low w/cm (< 0.25), dosages often exceed amounts recommended by the HRWRA manufacturers. Not all HRWRAs have the same water-reducing capability, and an indicator of this is the amount of solids content of the HRWRA. Generally, the higher the solids content, the greater the water reduction potential. The HRWRA dosage should be such that the concrete has a slump greater than 10 in. with fibers and the other materials remaining in suspension without segregation. UHPC “flow,” or the diameter of the resulting spread once the slump cone is removed, is commonly measured rather than the height of the drop in slump used for conventional concrete. Conventional water-reducing admixtures are not used in UHPC, as they are not effective. Air-entraining admixtures are also not used because the exceptionally low permeability of UHPC prevents moisture ingress and transport that cause deterioration from freeze–thaw cycling. Set retarders or slump-retention admixtures can be used for longer haul times or when casting in warm temperatures.

5 Commercial or Proprietary UHPC

There are several commercial or proprietary UHPCs available on the market that exhibit great performance and fit a wide variety of needs, ranging from architectural, transportation, structural, and force protection applications. These materials often come with optimized proportions that are relatively easier to produce with onsite technical representation from the manufacturer.

The exact composition of commercially available UHPC mixtures is not known, as they are patented by the companies that produce them. However, the constituent materials used to make commercial UHPCs are similar to those commonly found in traditional concrete or nonproprietary UHPC made with local materials. These include portland cement, fine aggregate, chemical admixtures, SCMs, and water. However, these commercial UHPC mixtures are unique because they require very careful selection of the quantities of each material, particle size distribution, and specific chemical admixtures.

The drawback for these commercial UHPCs is that logistics and costs can often extend to two to three times or greater than that of nonproprietary UHPC made with local materials.

Also, the general approach used by the commercial companies is the precast production of the finished product of UHPC in the element required, such as a bridge beam or component. The costs for a finished product that is precast and shipped to the construction site for fitting into the structure being built can exceed many times the costs of conventional concrete. However, the service life of UHPC elements will exceed that of conventional concrete and should be taken into account for overall cost calculations.

6 Mixture Proportioning

There are currently no standard proportioning processes to follow, and the design of UHPC mixtures remains largely empirical. Mixture proportioning is generally based on particle packing theory, whereby voids between larger particles are filled by smaller particles, creating a dense matrix. More laboratory trial batches are necessary to proportion UHPC than are required for conventional concrete. Once a trial mixture has been selected, field testing with production-size batches is recommended. The water demand and/or admixture dosage can vary from that determined in the laboratory. Production and quality control measures must be enhanced when producing UHPC. Aggregate moistures should be checked frequently, and admixture stockpiles should be fresh. Silica fume is difficult to put into silos, and fibers are typically batched manually, so proper procedures should be in place to efficiently batch these materials accurately and safely. It is best to conduct test placements with the equipment and personnel that will be conducting the full-scale operations.

7 Material Handling

The temperature of all ingredients should be kept as low as possible before batching UHPC to prevent overheating when mixing. Delivery time should be reduced to a minimum and special attention paid to batching and discharge to avoid having trucks waiting to unload. Extended haul times can result in a significant increase in temperature and loss of slump. Weather should be checked frequently, and night placements can be advantageous if outside temperatures begin to rise above ~85°F. Provisions to lower the initial temperature, such as using chilled water, are helpful; however, ice and/or liquid nitrogen should be avoided. The low w/cm combined with a high water demand make mixing UHPC with ice difficult. The slow melting of the ice produces extended wetting or break-over times that can vary and are difficult to control. Liquid nitrogen has not been used in production of UHPC, and potential side effects have not been studied.

8 Mixing

The energy required to mix UHPC is generally higher than that required to mix conventional concrete. The majority of proprietary, precast, and/or "finished product" UHPCs are mixed using high-shear mixers commonly found in precast concrete facilities. However, UHPC has been made using conventional ready-mixed or revolving-drum concrete trucks. The use of the revolving-drum mixers greatly increased production and allowed the user to produce the larger articles from one batch instead of from multiple smaller batches using a smaller high-shear mixer.

In their infancy, UHPCs were often called reactive powder concretes (RPCs) due to the powder-sized constituent materials and the resultant slow wetting process between the time of water addition and the material's "breaking over" or becoming fluid. Extended mixing times are to be expected and must be considered when casting large items that require more than one batch of UHPC. UHPC can be mixed in standard concrete trucks or batched in high-shear central plants and dispensed into a concrete truck for transport.

The order in which materials are loaded and mixed may vary, but it is generally recommended that the dry materials be "dry mixed" first, followed by the addition of water and admixtures. Because of the bulking seen when blending the dry materials, mixing chambers are usually loaded to only half of the mixing capacity of the particular mixer being used. Once the concrete reaches a fluid consistency, the fibers are added and mixed. This method promotes dispersion of the very fine particles and fibers, both of which tend to agglomerate.

When discharging the material, it is best practice to keep the flow of concrete at a slow and steady pace to minimize material handling and allow self-consolidation. If at any point the placement must pause, it is best to keep the material stirred or mixing slowly to avoid drying or plastic shrinkage.

9 Preparation for Placing

Preparation for placing UHPC should include extra precautions due to added difficulties in batching the material. Aggregate moisture contents should be measured frequently, and admixture dispensers and water meters should be monitored closely. Plans should be in place for manually batching all materials that cannot be included in the automated batching system (i.e., silica fume and fibers). Extra finishers are required due to the shortened effective working time for these mixtures. Care must be taken to not over- or underfill the formwork, as the high viscosity and cohesiveness make screeding more difficult. Formwork should be overdesigned and reinforced to account for high hydraulic pressure of the fresh concrete. The high fluidity and long set times put a substantially higher amount of stress on formwork than conventional concretes do. UHPC transport must be done at volumes ~25 percent lower than what the truck allows to prevent material spillage during transport, especially in hilly terrains. At least 10 percent of the UHPC can be expected to stick to the inside of the mixer or concrete truck. Proper planning, skilled laborers, adequate equipment, extra materials, and stand-by equipment are all essential to a successful UHPC placement.

10 Placement

The self-consolidating nature of UHPC can make many aspects of placement easier. Self-consolidation reduces the amount of spreading required; however, any spreading necessary will be more difficult because of high viscosity and fiber reinforcement. Other actions like screeding are also more difficult for the same reasons, and care must be taken during placement so as to not overfill the formwork. High temperature or wind can cause the concrete to form a dried-out layer called “elephant skin” that can lead to unintended cold joints during placement. If layering is detected during placement, effort should be made to vibrate the layers together in order to avoid unintended joints. Once screeding is complete, the concrete surface should be kept wet to avoid plastic shrinkage. The immediate covering of all exposed flatwork surfaces with an evaporation retarder is encouraged.

11 Workability

UHPC is a fluid, self-consolidating mixture with high viscosity or cohesiveness. General behavior is more akin to a “sticky” sanded grout or mortar mixture than it is to conventional concrete. Due to high dosages of HRWRA, set times are often extended beyond what is expected for conventional concretes. However, working times for UHPC are typically lower than those for conventional concretes despite the extended set time. The mixture should be easy to vibrate and workable enough to pass through spaces between reinforcement; however, vibration with a penetrating vibrator should be avoided if possible because it may cause fiber alignment and affect the directional properties of the hardened concrete. Fiber reinforcement will make spreading, shoveling, and screeding more difficult, so care must be taken when filling forms to minimize the amount of fresh movement required.

12 Surface Finishing

Floating and troweling are helpful when finishing UHPC, but a surface more rough than conventional concrete is to be expected. Many UHPC surfaces receive only a bull-float finish as an acceptable final finish. Timing for these finishing actions is typically extended 1 to 2 hr beyond what is expected for conventional concretes due to high dosages of HRWRA. It is common for fibers to poke out of the finished concrete. If steel fibers are used, some light grinding after curing may be necessary when traffic or foot traffic is expected. Other finishing methods, like a broom finish, are difficult to complete and should be avoided. If a smooth finish is desired, it may be best to design the article such that the exposed surface for the finished concrete is a formed surface. If the placement method is cast-in-place, a smooth surface can still be attained, but skilled finishers are required.

13 Curing

During the finishing and throughout the curing process, UHPC must be kept wet to avoid plastic shrinkage cracking. Curing compounds are permitted, but a saturated surface is preferred. High cement loadings lead to high exothermic heat evolutions, so insulation may be required to minimize thermal gradients within the UHPC after placement. Insulation would typically be added after final set between 6 to 8 hr after placement.

Very similar to silica fume concrete, plastic shrinkage cracking can occur in UHPC rapidly if surface drying occurs. The high silica fume contents combined with low amounts of water mean no bleed water is available to rewet the surface when evaporation occurs. This problem may be exacerbated in conditions of high temperature, low humidity, or high wind velocity. A light fog spray of water should be used to keep surfaces from drying between placement and finishing operations. Also, a sheet material can be used to cover the surface to reduce evaporation. It is best practice to use light-colored sheeting as opposed to dark materials that absorb heat. Moist curing should begin immediately after finishing and should continue until either elevated temperature curing begins or 7 to 14 days have passed if ambient temperature curing is specified. Chemical evaporation retarders have been found to work well in preventing early plastic shrinkage cracking.

It is common for UHPC to have specifications for either ambient or high-heat curing. During ambient curing, the concrete should be kept wet for at least 14 days after placement. High-heat curing can involve either wet or dry heat and consist of temperatures up to 190°F. Dry heat is generally accomplished with an oven, and wet heat uses a steam generator. Wet heat or steam curing is more common. Best practice is to keep the UHPC wet during an ambient curing period before the heat curing begins. Effort should be made to control the rise and fall of the concrete temperature during high-heat curing to prevent thermal shock and potential cracking. After heat curing is complete, the concrete no longer requires additional curing methods. Heat curing does not increase the strength of the concrete; it only helps the concrete reach its ultimate strength more rapidly.

14 Testing of Hardened Specimens

There are a limited number of standardized test methods specifically for UHPC. Most test methods for measuring hardened UHPC properties are the same as those for conventional concrete but with some modifications. ASTM C1856 (2017a) provides guidance for these modifications.

Compressive strength is measured by testing in accordance with ASTM C39 (2021a), but the loading rate is increased to reduce the testing times. Cylinder ends should always be ground due to difficulties incurred by sulfur capping and the wear on and failure of neoprene caps at higher loads. Any size cylinder or cube is permitted as long as the size of the specimen is at least three times the length of the largest fiber reinforcement. Testing equipment capacity must be considered when determining the specimen size. High compressive strengths of large specimen sizes mean very high peak loads must be reached in order to fail the specimen.

Flexural strength is best measured in accordance with ASTM C1609 (2019) for fiber-reinforced concrete. The most important behavior to measure is the postyield load-carrying capacity otherwise known as toughness. This means the testing duration should continue well beyond some of the limits established in ASTM C78 (2021b) for conventional concrete.

The static modulus of elasticity and the splitting tensile strength can be measured in accordance with ASTM C469 (2014) and ASTM C496 (2017b), respectively, but expect potential difficulties during modulus testing. The high UHPC hardness can lead to the strain gauge cage slipping during testing.

To effectively characterize the tensile behavior of fiber-reinforced UHPC, direct tension testing is used. These methods are especially important for capturing the postcracking behavior of UHPC, and they utilize either dog-bone-shaped specimens or prisms. The direct tension test method developed by FHWA (Russell and Graybeal 2013) is expected to be standardized in the future.

15 Advantages and Limitations

Because UHPC is usually also fiber-reinforced concrete, it has the same advantages and limitations as those already listed in the EM under the section for fiber-reinforced concrete. However, the matrix of UHPC is different from that of conventional concrete, and with these differences come different properties.

The high cementitious materials content combined with the addition of admixtures and fibers makes UHPC a much more costly material to produce than conventional concrete. However, due to its dense, impermeable matrix and postcracking behavior, some of the increased upfront costs associated with UHPC may be offset by an overall reduction in concrete volume, faster construction, and superior durability compared to conventional concrete. UHPC is virtually insusceptible to common concrete deterioration mechanisms that are driven by moisture transport, such as freeze-thaw cycling and alkali-silica reaction (ASR), resulting in fewer maintenance activities and extended service life. Additionally, the initial costs of employing UHPC may be reduced by optimizing its use. For example, UHPC may be used in key areas of a structure where enhanced durability, strength, and/or performance is needed while utilizing conventional concrete in the remaining parts of the structure.

Another limitation of working with UHPC is the lack of mixture and structural design guidance. Nevertheless, the current state of UHPC research combined with engineering expertise makes successful designs achievable. Several models, many of which are based on particle packing theory, exist for proportioning UHPC mixtures. In structural design, the biggest difference between designing with UHPC and designing with conventional concrete is the consideration of the tensile capacity. To date, there are no American design specifications or guidance for UHPC; sections of ACI 318 (2019) and AASHTO LRFD Bridge Design Specifications (2017) may be applied or modified for structural design of UHPC. Other countries—such as France, Japan, Germany, and Switzerland—already have guidance documents, and guidance development is underway in organizations such as the International Federation of Structural Concrete (*fib*), ACI, and International Union of Laboratories and Experts in Construction Materials, Systems and Structures.

References

AASHTO (American Association of State Highway and Transportation Officials) Highway Subcommittee on Bridges and Structures. 2017. *AASHTO LRFD Bridge Design Specifications*. Washington, DC: AASHTO.

ACI (American Concrete Institute). 2019. *Building Code Requirements for Structural Concrete*. ACI 318-19. Farmington Hills, MI: ACI.

———. 2018. *Ultra-High Performance Concrete: An Emerging Technology Report.* ACI 239R-18. Farmington Hills, MI: ACI.

API (American Petroleum Institute). 1997. *Recommended Practice for Testing Well Cements*. API RP 10B. Washington, DC: API.

ASTM (American Society for Testing and Materials) International. 2007. *Standard Specification for Portalnd Cement*. ASTM C150-07. West Conshohocken, PA: ASTM International.

———. 2014. *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. ASTM C469/C496M-14e1. West Conshohocken, PA: ASTM International.

———. 2017a. *Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete*. ASTM C1856/C1856M-17. West Conshohocken, PA: ASTM International.

———. 2017b. *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM C496/C496M-17. West Conshohocken, PA: ASTM International.

———. 2019. *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)*. ASTM C1609/C1609M-19a. West Conshohocken, PA: ASTM International.

———. 2021a. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.* ASTM C39/C39M-21. West Conshohocken, PA: ASTM International.

———. 2021b. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. ASTM C78/C78M-21. West Conshohocken, PA: ASTM International.

———. 2021c. *Standard Specification for Portland Cement.* ASTM C150/C150M-21. West Conshohocken, PA: ASTM International.

Japanese Society of Civil Engineers. 2008. "Recommendations for Design and Construction of High Performance Fibre Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC)." *Concrete Engineering Series 82:113*.

PCA (Portland Cement Association). 2022. www.cement.org/learn/concrete-technology/concrete-design-production/ultra-high-performance-concrete.

Russell, H. G., and B. A. Graybeal. 2013. *Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community*. FHWA-HRT-13-060. McLean, VA: US Federal Highway Administration.

SETRA-AFGC. 2002. *Betons fibrés à ultra-hautes performances—Recommandations provisoires (Ultra-High Performance Fiber Reinforced Concretes—Interim Recommendations*. Service d'éetudes techniques des routes et autortoutes (SETRA)—Association Françcaise de Géenie Civil, Bagneux (AFGC). Bagneux, France: AFGC.

USACE (US Army Corps of Engineers). 1994. *Standard Practice for Concrete for Civil Works Structures*. EM 1110-2-2000. Washington, DC: USACE.

Additional resources for UHPC

This section contains additional resources for UHPC categorized by type. These publications help to further a general understanding of UHPC design and characterization, and they contain the international standards available at the time of this report's publication in addition to those mentioned within the text.

General references

Graybeal, B. A., and F. Baby. 2013. "Development of Direct Tension Test Method for Ultra-High-Performance Fiber-Reinforced Concrete." *ACI Materials Journal* 110(2):177.

Green, B. H., R. D. Moser, D. A. Scott, and W. R. Long. 2014. "Ultra-High Performance Concrete History and Usage by the Corps of Engineers." *Advances in Civil Engineering Materials* 4(2):132–143.

Scott, D. A., S. G. Wood, B. P. Songer, T. Mack, B. H. Green, E. Hackbarth, C. N. Downey, K. E. Walker, and A. J. Tillotson. 2023. *Development and Characterization of Ultra-High Performance Concrete for the Rehabilitation of Navigation Structures*. ERDC/GSL TR in progress. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Design guidance

Gowripalan, N., and R. I. Gilbert. 2000. *Design Guidelines for Ductal Prestressed Concrete Beams*. Sydney, Australia: The University of New South Wales.

NF P18-470. 2016. *Ultra-High Performance Fibre-Reinforced Concrete–Specifications, Performance, Production, and Conformity*. Paris: AFNOR (Association Francaise de Normalisation).

NF P18-451. 2018. *Execution of Concrete Structures—Specific Rules for UHPFRC*. Paris: AFNOR.

NF P18-710. 2016. *National Addition to the Eurocode 2–Design of Concrete Structures: Specific Rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC).* Paris: AFNOR. Schmidt, M. 2008. "Ultrahochfester Beton, Sachstandsbericht (Ultra-High Performance Concrete, State-of-the-Art Report)." *Deutscher Ausschuss fuer Stahlbeton.*

SIA 2052. 2016. *Recommendation: Ultra-High Performance Fibre-Reinforced Cement-Based Composites (UHPFRC) Construction Material, Dimensioning, and Application.* Lausanne, Switzerland: Swiss Federal Institute of Technology (EPFL) Structural Maintenance and Safety Laboratory (MCS).

Acronyms and Abbreviations

Term	Definition
ACI	American Concrete Institute
API	American Petroleum Institute
ASR	Alkali-silica reaction
ASTM	American Society for Testing and Materials
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
EM	Engineering manual
ERDC	Engineer Research and Development Center
FHWA	Federal Highway Administration
HRWRA	High range water reducing admixture
NavSys	Navigation Systems Research Program
NMSA	Nominal maximum size aggregate
PCA	Portland Cement Association
RPC	Reactive powder concrete
SCM	Supplementary cementitious materials
UHPC	Ultra-High Performance Concrete
USACE	United States Army Corps of Engineers
w/cm	Water to cement ratio
WRA	Water reducing admixture

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14. ABSTRACT

Ultra-high performance concrete (UHPC) is a relatively modern class of concrete with properties that include very high compressive strengths, increased tensile strengths, very low permeability, and superior durability compared to conventional, normal-strength concrete. As research of this material continues to progress, its applications under both military and civil works categories expand. However, mixture and structural design guidance using UHPC is limited, particularly in the United States. This special report provides an overview of UHPC as initial guidance for the US Army Corps of Engineers (USACE) so that the material may be more easily utilized in civil works infrastructure. The information contained in this report is based on years of experience researching and developing UHPC at the US Army Engineer Research and Development Center (ERDC) and is intended to be a basis for the incorporation of this material class into USACE Engineer Manual (EM) 1110-2-2000, *Standard Practice for Concrete for Civil Works Structures,* when it is next updated.

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