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Ultra-High Performance Concrete History and Usage by the Corps of Engineers

Reference

Green, Brian H., Moser, Robert D., Scott, Dylan A., and Long, Wendy R., "Ultra-High Performance Concrete History and Usage by the Corps of Engineers," *Advances in Civil Engineering Materials*, Vol. 4, No. 2, 2015, pp. 132–143, doi:10.1520/ACEM20140031. ISSN 2165-3984

ABSTRACT

The U.S. Army Engineer Research and Development Center (ERDC) has conducted research on ultra-high performance concretes (UHPCs) since the late 1980s. The primary focus has been on military and civil works infrastructure applications. The research included the development of a UHPC material called Cor-Tuf Baseline, which includes several derivatives including a patented material. This paper presents the ERDC's historical experience with UHPCs, including constituent materials, laboratory-scale production, and heat treatment, typical microstructure, and pathways for scaling up production. Case studies are also presented on ongoing research focused on the use of fiber-reinforced UHPCs for repair and retrofit of armor plate systems in U.S. Army Corps of Engineers (USACE) inland navigation civil works infrastructure and ongoing long-term field durability testing at the Treat Island Natural Weathering Station near Eastport, ME.

Keywords

UHPC, RPC, VHSC, cor-tuf, durability, USACE, ERDC

Manuscript received July 19, 2014; accepted for publication October 20, 2014; published online November 19, 2014.

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Introduction

The U.S. Army Corps of Engineers (USACE), U.S. Army Engineer Research and Development Center (ERDC), has been investigating the use of ultra-high performance concrete (UHPC) for over three decades. From investigating the use of UHPC as impervious sewer and culvert pipe [1] to investigating the use of UHPC as a repair material for lock walls that are subjected to barge impact, the uses of UHPC in support of the USACE mission has steadily increased.

ERDC HISTORICAL RESEARCH AND DEVELOPMENT ON UHPCs

Starting in the late 1980s, researchers in the then Concrete and Materials Division, Waterways Experiment Station, now the ERDC, began investigations into the uses of UHPC for a variety of customer needs, and therefore, separate investigations into UHPCs were initiated by different researchers.

Working under the auspices of the USACE Construction Productivity Advancement Research (CPAR) project and working with private partner HDR Engineering, ERDC researchers Roy L. Campbell Sr. and Edward F. O'Neil investigated a UHPC called Reactive Powder Concrete (RPC) 200. The RPC 200 was described as "...formulated to optimize those properties that are beneficial to, and minimize those properties that are detrimental to, strength, durability, permeability, and toughness of concrete" [1]. This research was originally performed "...to develop and demonstrate the technical viability of using a RPC mixture for producing precast sewer, culvert, and pressure pipes and precast piling with the ultimate goals of gaining construction industry acceptance and implementing wide-scale commercial fabrication of these products within 3 years" [1].

The RPC 200 mixture proportion was developed by Bouygues S. A. and was first reported in the literature by Pierre and Cheyrez [2]. As noted by the name RPC, this class of UHPC mixtures is produced with all constituent materials (excluding fibers) being "powder-sized" or powders, generally less than 1 mm. Because of their powdered nature, high-shear mixing is generally the only acceptable and economically viable method used to produce these types of UHPCs.

Some of the earliest work performed by the ERDC researchers in the area of concrete mixtures that we now know as UHPCs occurred in the late 1980s. At that time, ERDC researchers embarked on a research program to produce "very high-strength concretes" for use in hardened facilities to make them less vulnerable to projectile penetration and ground shock. Messrs. Donald M. Walley and Billy D. Neeley of the then Concrete and Materials Division, Waterways Experiment Station (WES), now the ERDC, were tasked with the development of a high-strength concrete mixture that was to, "...achieve 30 000 psi unconfined compressive strength [3]," and be made with, "readily-available materials using conventional truck mixers [3]."

Readily available materials were defined as those that could normally be found at any concrete production facility. Other studies supporting the use of high-strength concretes to protect hardened structures were ongoing and studied concretes with unconfined compressive strengths that ranged up to 103 MPa (15 000 psi). Since conventional construction during this time period was reporting

70 MPa (10 000 psi) as high-strength concrete, the goal of a 207-MPa (30 000-psi) concrete was a lofty goal.

Evaluating papers found in open literature by Bache [4] and others, Walley and Neeley [3] worked independently from other researchers at the ERDC and developed a concrete material they named very-high-strength concrete (VHSC). Over approximately a five-year period, a large number of constituent materials such as portland cement (including portland cements meeting criteria as set forth by both ASTM and the American Petroleum Institute (API) for oil-well cements), silica fume, concrete sand, crushed silica sand (also called silica flour), and high-range water reducers were proportioned into several hundred UHPC mixtures, before a “mixture of choice” was selected that met the specified criteria. Various steel fibers with a variety of aspect ratios were also added to the mixtures to increase tensile properties. It was also determined that inundating the test specimens in a water bath placed in an oven and then curing at 90°C provided increases in both flexural and compressive strengths.

The VHSC mixture was produced using a conventional truck mixer, and a variety of test specimens were cast for varying projects. Unfortunately, due to Walley’s untimely death, this work remains largely unpublished. However, Neeley and Walley published an article describing the VHSC mixture and its component materials in 1995 [5] and another article by Cargile et al. in 2002 [6].

RECENT RESEARCH ON UHPCS

Beginning in the late 1990s, Dr. Edward O’Neil and Dr. Beverly DiPaolo, both of the ERDC, continued the work of Walley and Neeley by building on and refining the VHSC class of UHPC mixtures. O’Neil, in his Ph.D. dissertation [7], gave an excellent accounting of VHSC, the philosophy and science behind it, and the direction that his and DiPaolo’s research had addressed until that time.

O’Neil and DiPaolo’s research in this area sought to increase the strength of VHSC and included research on optimizing the constituent materials, including the portland cement, silica fume, crushed silica or silica flour, chemical admixtures, and other micro- and nano-scale additives. The methodology of curing was also examined, including different combinations of water curing at ambient conditions, inundated heated water curing at 90°C, and/or oven dry heating at 90°C. This research also explored efforts to increase the toughness of VHSC by optimizing the use of steel fibers, wollastonite microfibers, and silica-ceramic microspheres. From a material standpoint, the continued research on the VHSC class of mixtures conducted by O’Neil and DiPaolo led to the development of a family of UHPC mixtures now commonly referred to as Cor-Tuf. One of the Cor-Tuf mixtures incorporated silica-ceramic microspheres, which led to the issuance of a patent in 2010.

CURRENT INITIATIVES

Another Cor-Tuf mixture, named “Cor-Tuf Baseline,” was developed to serve as, and is currently considered by ERDC to be, a “laboratory standard” UHPC mixture that can be reproduced for various projects and exhibit the same physical properties with minimal batch-to-batch variability. The goal of Cor-Tuf Baseline was to minimize batch-to-batch variations as much as possible and to supply other ERDC researchers with a UHPC mixture that would be the same, no matter when it was

produced. To that end, the constituent materials that comprise Cor-Tuf Baseline must be obtained from the same vendors, source material location, manufacturing facility, etc., to maintain this standardization goal. Another feature of Cor-Tuf Baseline is that a revolving-drum mixer can be used to produce the mixture. The use of the revolving-drum mixer greatly increased production and allowed ERDC to produce the larger test articles from one batch instead of from multiple smaller batches using a smaller high-shear mixer. This allowed an expansion of the production of test articles to be produced for a variety of research projects within the ERDC.

The current Cor-Tuf Baseline formulation has been and is currently being utilized in a variety of research focus areas including Military Engineering and Civil Works (CW) infrastructure applications. Example applications for UHPC in CW infrastructure include repair and retrofit of armoring systems subjected to vessel impacts and also potential applications for retrofit of underwater areas of structures subjected to erosion and abrasion from high velocity flows (e.g., stilling basins, baffle blocks, and end sills in lock and dam structures). Additional research on Cor-Tuf Baseline is also currently underway (along with VHSC and RPC formulations) at the Treat Island Natural Weathering Station to investigate long-term field durability when subjected with wet/dry, freeze/thaw, and corrosion conditions.

The following sub-sections provide summaries of ongoing long-term field durability research on UHPCs at Treat Island and a case study on a recent application of UHPC for repair of armoring systems in USACE inland navigation structures.

Long-Term Field Durability of UHPC at Treat Island

To better understand the durability of cementitious materials in a severe marine environment, the USACE through its ERDC, has operated the Treat Island Natural Weathering Exposure Station located in Cobscook Bay near Eastport, ME for over 75 years. **Figure 1** shows recent photographs taken in 2013 of the facility. Treat Island is located near the Bay of Fundy with daily tides that vary by as much as 6.7 m (22 ft), which inherently imposes a unique combination of natural severe environmental conditions that are ideally representative of severe field exposure conditions

FIG. 1

Photograph of Treat Island Natural Weathering Station at mid-tide elevation during Summer of 2013. Pier and mid-tide wharf shown in background. Beach shown in foreground.



[8]. During the winter, Treat Island test specimens are subjected to between 100 and 160 freeze-thaw cycles and various durations of wet/dry cycling depending on the elevation of the specimens.

Treat Island's location makes it ideal for exposing concrete and concreting materials to severe natural weathering. Its effect is to provide a natural field laboratory where no size limitation is placed on the exposed specimens. The alternating conditions of immersion of the specimens in sea water then exposure to cold air provide numerous cycles of freezing and thawing of the concrete during the winter. The effect of the relatively cool summers is to lessen, in general, autogenous healing and chemical reactions in the concrete [8].

The ultimate test of the durability of concrete is its performance under the exposure conditions in which it is to serve. Although laboratory tests yield valuable indications of probable durability, the potential disrupting influences in nature are so numerous and variable that actual field exposures are highly desirable to assess the durability of concrete when exposed to natural weathering. Cyclic inundation of saltwater and air drying also simultaneously subject test specimens to chloride intrusion, wetting and drying, abrasion-erosion, and salt crystallization pressures, in addition to cyclic freezing and thawing [8].

Because the nature of UHPC mixtures was believed to be nearly impermeable, it was believed that they would be highly durable and resistant to chloride ingress and cycles of saturated freeze-thaw damage, even when exposed to the severe environment at Treat Island.

EXPERIMENTAL PROGRAM

Starting in 1995, a series of different types of UHPC were placed at the mid-tide level of the marine exposure site at Treat Island [9]. The first series of UHPC mixtures were VHSC beams (152 by 152 by 533 mm) produced by Walley and Neeley at the ERDC and placed at Treat Island in 1995. The VHSC incorporated API Class H Oil well cement, silica fume, silica flour, and siliceous concrete sand with a maximum particle size of 4.75 mm, along with a high-range water reducing admixture (HRWRA) to allow complete mixing and placement of beam specimens. Hook-ended steel fibers 30 mm in length and 0.55 mm in diameter were used in these mixtures. The second series were RPC 200 beams (152 by 152 by 533 mm) produced by Campbell and O'Neil in 1996. The RPC 200 was produced with API Class H oil well cement, silica fume, silica sand with a maximum particle size of 0.6 mm, HRWRA, and metallic fibers 13 mm in length and 0.16 mm in diameter. To evaluate corrosion protection, the three RPC 200 beams contained 13-mm-diameter steel reinforcing bars with cover depths of 25, 19, and 10 mm. A summary of the mixture proportions for the first and second series of specimens placed at Treat Island is provided in **Table 1**. Photographs of typical test specimens are shown in **Fig. 2**.

At yearly intervals, the concrete specimens were subjected to a visual inspection and measurement of resonant frequency and ultrasonic pulse velocity. Samples from each series were retrieved after 5 to 15 years of exposure for testing in the laboratory at the University of New Brunswick (UNB) [9]. The testing consisted of compressive and flexural strengths, static modulus of elasticity, electrical properties, chloride profiling, corrosion activity of reinforcing steel (if present), and microstructural evaluation of the concrete [9].

TABLE 1Mixture proportions (kg/m^3) of UHPC [9].

Material	UHPC Type	
	RPC 200	VHSC
Cement	942	796
Silica Fume	236	199
Silica Flour	—	110
Fine aggregate	1036	897
Fibers	160	235
Water	136	207

Results and Discussion

Two beams were retrieved in 2009 at an age of 12 years for testing at UNB [9]. A visual assessment of the beams showed negligible surface damage from freeze/thaw (after 1000–1920 cycles) and only minimal corrosion of steel fibers that were directly exposed on the surface. Chloride profiles were measured and indicated a significant reduction in chloride penetration. **Figure 3** shows a comparison between chloride penetration of a high performance concrete (HPC), produced with 8.5 % silica fume and w/cm of 0.33, and an RPC/UHPC specimen at similar ages. In the case of the HPC, chlorides were present at appreciable levels for corrosion to a depth of approximately 20 mm (0.05 % chloride threshold level for corrosion). Chloride penetration in the RPC specimen was reduced by approximately an order of magnitude when compared to HPC with an appreciable amount of chloride only present in the surface 5 mm of material. Of course, chloride penetration into a normal strength concrete (NSC) would be considerably higher when compared to both the RPC and HPC. These results portend to the enhanced durability in UHPCs along with their increased compressive and tensile strengths.

FUTURE RESEARCH

To build on this previous work, an additional phase of long-term field durability testing on UHPCs was initiated in 2013. The focus of this work is on the current Cor-Tuf Baseline formulation being used by ERDC. Beam specimens were fabricated using the Cor-Tuf Baseline UHPC formulation with steel fiber reinforcement both with and without a standardized curing regime applied. Three beam specimens of

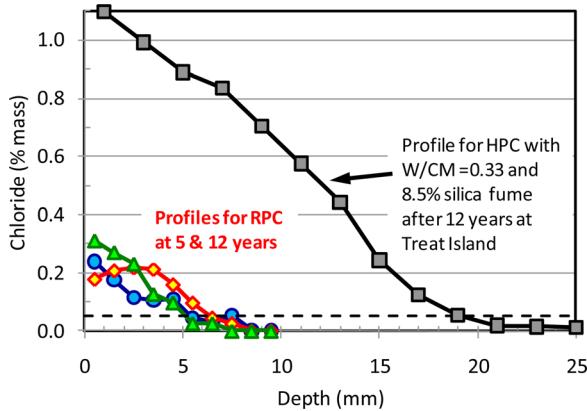
FIG. 2

Photographs of VHSC/UHPC specimens taken during periodic inspection.



FIG. 3

Chloride concentration profiles for RPC and HPC following 12 years of exposure at the Treat Island Natural Weathering Station (from Ref. [9])



each curing regime were placed on the mid-tide elevation of the pier at Treat Island along with baseline NSC and other concrete specimens including concretes with alternative non-portland cement-based binders. We anticipate extracting these samples after exposure and forensically examining them to assess their deterioration from natural weathering.

Case-Study: UHPC for Retrofit of Armoring Systems in Inland Navigation Structures

USACE owns and operates one of the largest inventories of water resources and inland navigation structures in the world, with 207 inland navigation structures that are responsible for the movement of approximately 600 million tons of commerce annually. Much of this “aging” infrastructure is well beyond its originally designed service life, with a mean time in service in excess of 50 years. One common component in these structures that is often damaged is the armoring system located on the inner walls of lock chambers that protect recesses and mechanical systems from vessel impacts. **Figure 4** depicts a damaged armor component near a miter gate recess in an inland navigation structure. Similar damage is seen on armor components protecting mooring buoys along lock chamber walls.

Since many repair materials (e.g., portland cement-based grouts) do not gain strength rapidly enough to maintain operability of the structure, these components

FIG. 4

Typical damage to vertical armor plate component at miter gate recess in inland navigation lock structure. Photographs taken in Summer 2013 at Newt Graham Lock and Dam, USACE Tulsa District.



often go unrepaired until periodic repair operations, resulting in subsequent risks to vessels from damaged armor and protruding anchorages.

Two potential solutions to this problem are:

1. Novel materials to rapidly repair damage that reduces the impact of the repair operation on inland navigation. This is the subject of ERDC research on rapid repair materials that is beyond the scope of this paper.
2. Use of materials to retrofit armor plate systems that increases the strength and impact toughness of these critical components, i.e., an ideal application for UHPC that warranted evaluation.

In order to assess the feasibility of using UHPC for retrofitting armoring systems to improve their performance, a laboratory-based study was initiated where simulated armoring systems were retrofitted with UHPC and tested for ultimate load carrying capacity. Following the laboratory-based study, a small field demonstration project was conducted using UHPC as one of many repair materials.

EXPERIMENTAL PROGRAM

Simulated armor plate repair test articles were prepared by first fabricating a concrete test block to mimic the armor plate corner with a rounded roughened surface. The concrete for the test block was a 27-MPa (4000-psi) structural concrete with steel fiber reinforcement to negate the need for reinforcing steel. Steel armor plates were affixed to the outer corner of the region to be repaired, and the appropriate repair material was used to infill the void between the steel armor plate and concrete test block. Repair materials included a portland cement-based grout, Cor-Tuf Baseline UHPC, and multiple variants of a calcium sulfoaluminate cement-based rapid repair grout material. **Figure 5** details the layout of the armor plate repair mock-up for laboratory-based testing.

Concrete test blocks were moist cured at 23°C for 28 days, followed by application of the appropriate repair material. The portland cement-based grout-control repair material was moist cured at 23°C for 28 days prior to testing. The Cor-Tuf Baseline UHPC was moist cured at 23°C for 28 days as opposed to the traditional high-temperature steam curing regime (80°C–90°C). The use of room temperature moist curing for the UHPC material was employed since the use of high temperature steam curing in the field would be difficult for these small placements. As a result, the UHPC repair material cured at room temperature achieved an unconfined

FIG. 5

Example armor plate retrofit mock-up for laboratory-based testing.

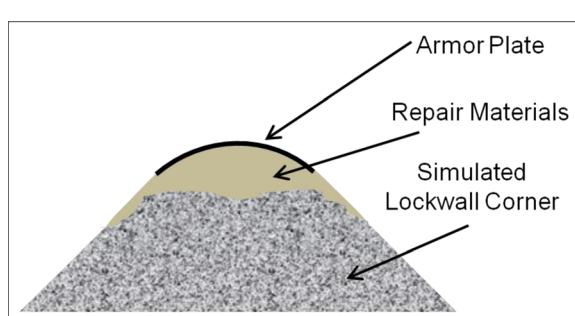


FIG. 6 Armor plate repair specimens following testing. Fiber reinforcement significantly reduced cracking and spallation of the repair material. (a) Non-fiber-reinforced specimen following testing. (b) Fiber-reinforced specimen following testing.



compressive strength of approximately 160 MPa (23 ksi) as opposed to the typical 200 MPa (30 ksi) achieved with high-temperature steam curing.

Following the specified curing regime for each repair material, specimens were tested for ultimate load-carrying capacity. Specimens were tested in compression, with compressive loads applied directly to the armor plate over a 15-cm (6-in.) length using a 2.2-MN (500-kip) universal testing frame. Compressive loads were increased at quasi-static displacement rates until the ultimate load carrying capacity was reached.

RESULTS OF LABORATORY-BASED TESTING

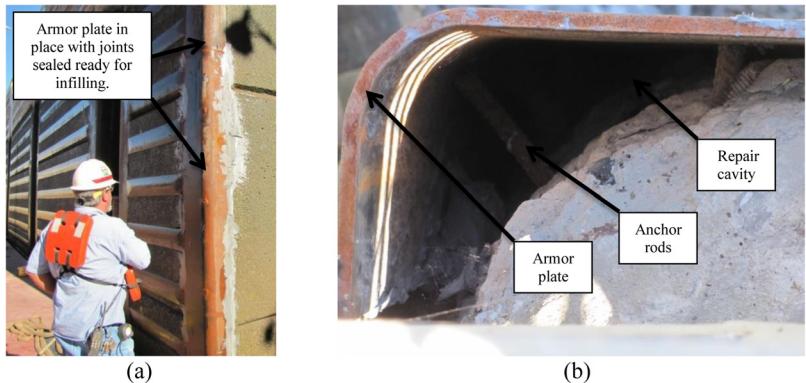
Test specimens failed in compression similarly to failures observed on armoring systems in the field. **Figure 6** depicts typical failures following compression testing of an armoring system repaired using repair material with and without steel-fiber reinforcement (1 % by volume). The use of UHPC resulted in an approximately 50 % increase in load carrying capacity when compared with the typical portland cement-based grout, with failures occurring at approximately 890 kN (200 kips). Testing performed with UHPC repairs made without the use of a surface mounted steel armor plate also provided similar compressive strength values. The addition of fibers in the UHPC also had a marked effect on the failure morphology. Non-fiber-reinforced grout exhibited extremely brittle modes of failure with extensive cracking and spalling. In the fiber-reinforced UHPC, small cracks were observed, but the repair maintained its integrity even after reaching the ultimate load-carrying capacity. Both results indicate the potential for improved performance if UHPC were to be used for armoring systems in inland navigation structures.

FIELD DEMONSTRATION PROJECT

In order to assess the feasibility of using UHPC, among other repair materials, for repair and retrofit of armoring systems, a small-scale field demonstration project was conducted at Newt Graham Lock and Dam near Tulsa, OK. This structure previously had repairs made with a portland cement-based grout that failed quickly due to vessel impacts before the repair had gained sufficient strength. Armor-plate

FIG. 7

Armor plate repair components prior to placement of repair material. (a) Armor plating prior to repair. (b) Armor plate cavity to be filled with repair material.



components were placed and secured using anchor rods embedded into the structure. Ports were added for the repair material to be placed. Two repair materials were demonstrated, i.e., (1) a fiber-reinforced pre-packaged UHPC, and (2) a fiber-reinforced calcium sulfoaluminate cement-based repair grout. Photographs of the area to be repaired prior to placement of the repair material are shown in **Fig. 7**.

UHPC was mixed on site using a grout mixer in a steel washtub. Following mixing, the UHPC was placed in the cavity behind the armor plate by pouring through ports cut into the surface of the armor plate. External vibration was applied using plate vibrators to consolidate the material after placement. **Figure 8** 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. Ambient curing temperatures ranged from 15°C to 21°C (60°F–70°F).

Along with the UHPC placement at Newt Graham Lock and Dam, armor plate repairs were made using typical portland cement-based grout, a calcium sulfoaluminate cement-based rapid repair material, and a two-part epoxy extended with fine aggregate. With multiple materials used for making the same repairs, this structure will serve as a test bed to demonstrate the long-term performance of these various repair materials.

FIG. 8

Placement of UHPC repair material in cavity behind armor plate. (a) Placement of repair material by pouring through ports. (b) Top surface of UHPC repair following placement in cavity behind armor plate. Shown in same orientation as **Fig. 7(b)**.



Conclusions

The U.S. Army ERDC has been involved with research on UHPCs since the late 1980s, with focus areas spanning from military engineering to unique applications in our civil works infrastructure. With their unique combination of high strength in compression and tension, high durability (as demonstrated by the work at the Treat Island Natural Weathering Station), and high toughness with the addition of fiber reinforcement, UHPCs lend themselves to many specialized applications in the concrete industry. While their expense remains high compared with other, more typical concretes, the mechanical properties and durability benefits often far outweigh the cost when used for applications that demand high performance. The armor plate repair and retrofit case study presented herein is just one example of a unique application of UHPC.

Future work on UHPCs at ERDC is anticipated to vary widely, from micro- and nano-structural modifications via characterization and modeling to scaling up fabrications for large-scale placements.

ACKNOWLEDGMENTS

The writers would like to acknowledge all of the assistance provided by multiple current and previous engineers, scientists, and technical support staff who developed the breadth of knowledge we have today on UHPCs. This document was approved for publication by Director, Geotechnical and Structures Laboratory, U.S. Army Engineer Research and Development Center.

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