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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

https://highways.dot.gov/research

Sprayable UHPC for Repair and Preservation

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FHWA Contact: Benjamin A. Graybeal, HRDI-40, 202-493-3122, benjamin.graybeal@dot.gov

INTRODUCTION

Due to its advantageous properties, including exceptional durability, ultra-high performance concrete (UHPC) is increasingly being used in North American transportation infrastructure for new construction and for preservation and repair of existing structures. The majority of the applications of UHPC involve pouring the UHPC into place—either with a self-consolidating UHPC or with a thixotropic UHPC that is vibrated and struck off with a vibrating screed after initial placement. Certain existing applications of UHPC—such as girder end repairs and wall and column repairs and protection—could benefit from the ability to spray UHPC into place. New or potential future applications of UHPC, such as bridge deck soffit repairs and culvert repairs or retrofits, could also benefit from sprayable UHPC. In these applications, spraying UHPC is typically less costly than pouring UHPC due to the elimination of formwork. Also, spraying UHPC allows the UHPC to be applied on a structure from any direction rather than the mixture being poured from above the structure and relying on gravity to distribute it, which can be restricted by obstructions such as a bridge deck.

Sprayed UHPC first appeared in Europe in the late 1980s and was used to strengthen and repair various structures. However, unlike common UHPC mixes of today, the UHPC mixes used at that time included fine aggregate particles exceeding 0.02 inch in diameter and did not always include steel fibers (Buitelaar 2018). In recent years and with the use of modern mix designs, sprayed UHPC has been used on multiple infrastructure projects in Europe; however, only a few demonstration or research projects have used sprayed UHPC in the United States. This TechNote presents some of the successes of sprayed UHPC in Europe and the United States and discusses some of the challenges of using it, thus aiming to encourage and facilitate its adoption in the United States. This technology shows great promise, given its potential to lower UHPC placement costs and enable new applications that can benefit from the properties of UHPC.

For more information on UHPC material properties and on other more common applications, the reader is referred to *Design and Construction of UHPC-Based Bridge Preservation and Repair Solutions*, as well as *Design and Construction of Field-Cast UHPC Connections* (Haber et al. 2022; Graybeal 2019).

TECHNOLOGY OVERVIEW

Sprayed Concrete

Sprayed concrete (also known as shotcrete or gunite) is a concrete placement technology frequently used with conventional concrete because of its many advantages for specific applications. Common applications of sprayed concrete are excavation and slope stabilization; protective lining of tunnels, culverts, and channels; and concrete repairs, especially on large vertical and overhead surfaces such as piers, walls, and deck soffits. Some of the advantages of sprayed concrete include:

- Lack of need for formwork.
- Complete flexibility of concrete placement direction and thickness.
- Ability to place concrete overhead.
- Good adhesion to substrate.
- Rapid curing.

To be successfully sprayed, concrete typically has a maximum aggregate size of 0.5-inch or smaller and is modified with various additives such as accelerators, superplasticizers, and pumping aids. Most sprayed concrete applications rely on a metal grid made from reinforcing bars or wire mesh installed in the placement area to help hold the sprayed concrete in place. This grid also reinforces the cured concrete.

Concrete can be sprayed using either a wet or a dry mix method. In the dry mix method, the combined dry ingredients are pneumatically pushed to the nozzle, where water and any liquid admixtures are added as the mixture is sprayed from the nozzle. In the wet mix method, the concrete and liquid ingredients are mixed in advance and then pumped to the nozzle. Compressed air is added at the nozzle to spray the concrete.

Successful concrete spraying depends heavily on the skill of the nozzle operator. For this reason, the American Concrete Institute (2023a, 2023b) has two shotcrete nozzleman certification programs—one for the wet mix method and one for the dry mix method.

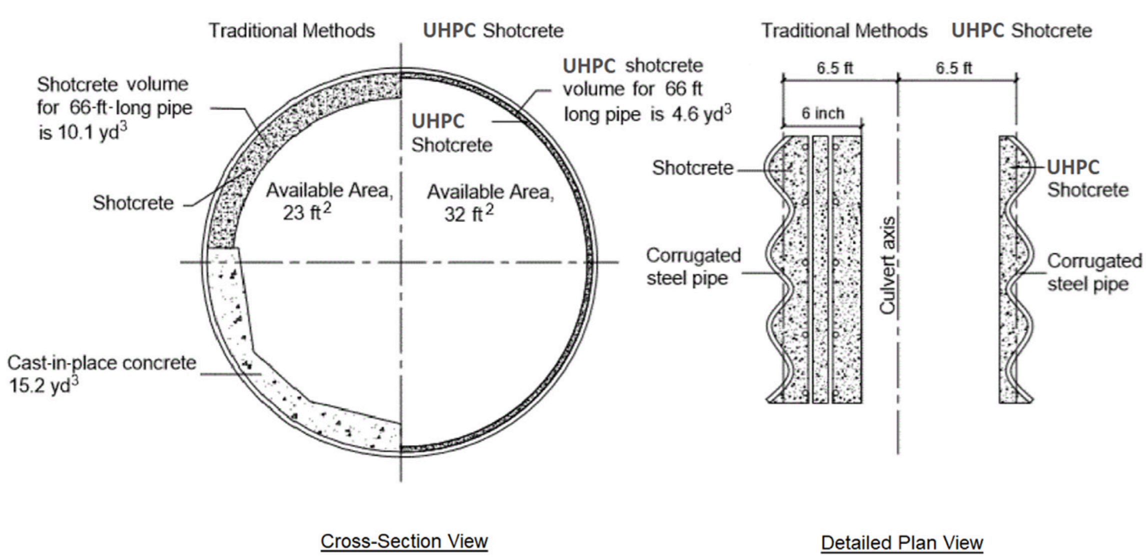
Sprayed UHPC

All the aforementioned advantages of sprayed concrete also apply to sprayed UHPC, including a rate of curing that is more rapid than the typical UHPC curing rate. Sprayed UHPC also experiences less rebound than sprayed conventional concrete due to its lack of coarse aggregate, meaning less material is wasted.

Current methods of spraying UHPC generally follow the wet mix method. Water is added to the UHPC dry mix in a suitable mixer, and once the proper material consistency has been achieved, steel fibers are added to the mix. When the fibers are uniformly dispersed, the UHPC mixture is pumped to the nozzle where compressed air is added to spray the UHPC.

Because of the advantageous material properties of UHPC, repairs made with sprayed UHPC can typically be performed with much less material compared with those with conventional concrete. This feature can be particularly important for culvert rehabilitation where maintaining hydraulic capacity is important. An example of the benefits of sprayed UHPC for a culvert is shown in figure 1.

Figure 1. Illustration. Comparison of sprayed UHPC versus conventional concrete for corrugated metal culvert rehabilitation (Doiron 2019).



Because of its strength, the comparatively thinner layer of UHPC applied to rehabilitate a culvert can often carry the culvert loads independent of the remaining existing steel culvert. In this scenario, concerns of continued deterioration of the original metal culvert can be alleviated. Furthermore, the thinness of the UHPC shell allows it to flex, much like the original metal culvert, to adapt to the surrounding soil. Finally, experience from Europe has indicated that the cost of rehabilitating corrugated metal culverts with sprayed UHPC is about the same as that for conventional rehabilitation solutions. However, rehabilitation with sprayed UHPC has multiple advantages over conventional rehabilitation solutions (Huynh, Petit, and Derimay 2019):

- The rehabilitation work does not require interruption of traffic above the culvert and requires only minimal work areas at the ends of the culvert.
- The duration of the rehabilitation work is reduced compared with other rehabilitation methods due to low volumes of material used and the use of a single technology.
- The thin layer of UHPC has a low impact on the hydraulic capacity of the culvert and provides good abrasion resistance.

Sprayed UHPC in Europe

In 2016, a UHPC supplier in Europe undertook a series of experiments to adapt their UHPC material to pumping and spraying with conventional piston-driven concrete pumps, with a focus on the rheology of the material. The supplier significantly revised the UHPC mix design compared to their typical self-leveling UHPC mix design (Trucy, Dobrusky, and Bonnet 2017; Doiron 2019).

A contractor partnered with the UHPC supplier in 2017 to carry out multiple tests of sprayed UHPC to rehabilitate corrugated steel culverts; validate the UHPC mix design, equipment, and application procedures; and create a quality control plan, using a thickness of UHPC that ranged between 1.2 inches and 2.4 inches (Huynh et al. 2017). After the successful test program, the contractor concluded that sprayed UHPC is an excellent method to rehabilitate deteriorated metal culverts and went on to subsequently rehabilitate many other culverts with sprayed UHPC.

Since 2018, multiple sprayed UHPC projects have been carried out in Europe to rehabilitate corrugated steel culverts (Gluzicki 2020; EGIS 2021; République Française 2022; Huynh, Petit, and Derimay 2019; Picaud 2019; Ministère Chargé des Transports [France Ministry of Transportation] 2019), rehabilitate two dams (Floquet and Teply 2022), and add a wearing surface for mining equipment (Riedigers 2022). These projects have used at least two different commercial UHPC products—one modified specifically for spraying, and one using the standard self-consolidating mix with adjustments only made to the quantity of one admixture to modify the flow characteristics.[1]

Sprayed UHPC in North America

To date in North America, sprayed UHPC has been limited to a few trials and research projects in the United States. A trial performed by a contractor using a conventional piston-driven concrete pump with a commercially available UHPC was successful, but some challenges occurred with the pump not being well adapted to UHPC.[2] A UHPC supplier that was not involved in that trial has recently announced the availability of custom-designed and fabricated equipment for pumping and spraying UHPC and has carried out a few successful trials and a research project (Hays 2022; Kulish and McDonagh 2022).

IMPLEMENTATION CHALLENGES

Spraying UHPC presents a few challenges that either do not exist when spraying conventional concrete or are more difficult to overcome with UHPC.

Pumping

The workability of UHPC is highly sensitive to heat. A commonly accepted upper temperature limit to maintain workability of fresh UHPC is 80 °F, although some UHPC mixes can tolerate higher temperatures (Graybeal 2019). UHPC typically heats up during mixing due to the internal heat of hydration and friction from the mixing operation. When UHPC is mixed in warm or hot weather, many UHPC suppliers displace some of the mixing water with ice to keep the fresh UHPC temperature below the upper limit, even when the mixture is not being pumped.

One of the challenges with pumping is that most concrete pumps add a significant amount of heat to the fresh UHPC. This scenario is largely due to the pistons in conventional concrete pumps pushing and pulling the concrete, creating significant internal friction. Sun exposure, especially on long pump hoses, can further increase the heat gain. A UHPC supplier may be able

[1] Laurent Boiron, Managing Director, UHPC Solutions Europe, in a telephone interview with Michael McDonagh, National Bridge Materials Specialist, WSP, January 18, 2023.

[2] Ibid.

to compensate for the heat gain and corresponding loss of workability by adjusting the mix before it enters the pump. However, experience has shown that this practice becomes increasingly challenging as ambient temperatures rise (McDonagh and Foden 2019).

Another challenge with pumping UHPC is the relatively high dosage of steel fibers present and the dimensions of the steel fibers. UHPC typically has a minimum fiber content of 2 percent by volume, which is much more than is typically used with conventional fiber reinforced concrete. Furthermore, the fibers used with UHPC are much smaller than those typically used with conventional fiber reinforced concrete and have a needlelike size and shape. The result is a tendency for the fibers to stick to the insides of hoses, leading to clogging. For the same reason, cleaning pumps and hoses after pumping UHPC is more difficult and time-consuming than after pumping conventional concrete.

A European company and a U.S. company have successfully sprayed UHPC and solved the pumping issue with different approaches. The European company trialed multiple conventional concrete pumps and determined that one particular concrete pump model on the market minimized the heat gain such that they could spray UHPC with it (Doiron 2019). The company then fabricated a customized UHPC mixing, pumping, and spraying machine, incorporating this pump to provide consistency in the process (Huynh et al. 2017; Huynh, Petit, and Derimay 2019). The U.S. company fabricated two customized UHPC mixing, pumping, and spraying machines. Rather than incorporating conventional piston-action concrete pumps, the U.S. company custom-fabricated pumps used squeeze pump technology, which practically eliminates any friction heat gain (Kulish and McDonagh 2022). The U.S. company also customized the hose couplings to reduce the likelihood of fiber clogging.

Equipment Type and Availability

The aforementioned challenges related to pumping show that the selection of pump equipment is critical to successfully spraying UHPC. Simply selecting any available concrete pump to spray UHPC appears to have a low chance of success. Thus, because of limited options for off-the-shelf pumps, the availability of suitable pumps is limited. In the near term, the best option may be to work with companies that have equipment that has successfully sprayed UHPC.

Some of the pump equipment and operating requirements determined from the European test programs using a piston-driven pump are as follows (Doiron 2019):

- A conventional piston-driven concrete pump must have a minimum piston cylinder diameter of 6 inches.
- Reductions in conveyance diameter from the pump to the hose must be progressive without abrupt changes.
- The pump requires an engine power of at least 75 hp to pump UHPC up to 130 ft without significant vertical elevation change.
- The pump line must first be primed with UHPC containing no steel fibers before pumping UHPC with steel fibers.
- The line must be cleaned after pumping UHPC by first pumping it with a mortar with no steel fibers and then cleaning it with water.
- The Doiron (2019) report offers recommendations on specific pump models that perform well for sprayed UHPC.

Material Formulation

The formulation of the UHPC material can play a role in the success of UHPC spraying. At least two commercially available UHPC products have been successfully sprayed with no or only minor modifications to the standard formulation: one using customized proprietary equipment that incorporates squeeze pump technology, and another using conventional piston-driven pumps (Kulish and McDonagh 2022).[3] However, another commercial UHPC supplier made significant modifications to their standard UHPC material formulation so that it could be successfully sprayed using conventional concrete pumps (Trucy, Dobrusky, and Bonnet 2017).

Expertise

UHPC mixing requires expertise and is typically handled or overseen directly by the UHPC supplier. Mixing expertise is even more critical when pumping and spraying UHPC, as the UHPC may require frequent modifications to maintain the desired workability. Furthermore, as with spraying conventional concrete, successful UHPC spraying is highly dependent on a skilled nozzle operator.

[3]Ibid.

Watertightness

Laboratory test data show that UHPC has extremely low permeability, which is one reason why it is used to rehabilitate bridge decks as it can effectively waterproof a deck (Haber et al. 2018). However, in culvert and tunnel applications where constant hydrostatic pressure may exist, special attention must be paid to the issue of watertightness where this quality is considered important. Some early applications of UHPC for tunnel rehabilitation have shown signs of water infiltration, although experts do not yet know whether water is infiltrating through the UHPC, or through connections, or even through potential cracks in the UHPC.

PROJECT EXAMPLES

Projects in France

Multiple corrugated metal culverts under roads and highways in France have been rehabilitated using sprayed UHPC. Two of the first culvert projects are presented in the following subsections. Other culverts in France (not discussed in this TechNote) have been rehabilitated with sprayed UHPC, including the A64 highway in Tarbes, France, with planned projects to rehabilitate and extend the Route Centre-Europe Atlantique (RCEA) highway culvert near Palinges and to rehabilitate an A450 highway culvert near Lyon (Gluzicki 2020; EGIS 2021; République Française 2022). Infrastructure owners also used sprayed UHPC to rehabilitate two dams over the Rhône river in the towns of Sauveterre and Caderousse (Floquet and Teply 2022). The contractors chose sprayed UHPC for the dam rehabilitations due to its speed of application versus poured UHPC and its durability versus conventionally sprayed concrete (Picaud 2019).

RCEA Highway (RN 70) Culvert in Ciry-le-Noble

The first project rehabilitated with sprayed UHPC was a culvert for the passage of cattle under the RCEA highway (RN 70), in Ciry-le-Noble, France (Huynh, Petit, and Derimay 2019; Picaud 2019). The culvert is 61 ft long with an interior height of 12.1 ft and was rehabilitated in 2018. The culvert contained significant areas of corrosion, creating the need for rehabilitation to maintain its structural integrity. One of the project constraints was to avoid reducing the interior clearance by more than 1.2 inches. A solution with conventional reinforced concrete would have reduced the clearance by more than 6 inches. Another project goal was to design the rehabilitation such that all the dead and live loads could be carried independent of the steel culvert.

The selected rehabilitation consisted of a layer of sprayed UHPC that was 1.2 inches thick over the ridges of the corrugated steel (and deeper over the valleys). Figure 2 shows the UHPC being sprayed on the corrugated steel. Reinforcing steel was only placed around the connections of the steel culvert segments to ensure mechanical continuity across the connections. A total of approximately 27 yd^3 of UHPC were sprayed. After spraying, the UHPC was smoothed out with large straightedges. Finally, after curing, a mortar finishing coat was added to the culvert sides to smooth them out and cover protruding fibers. The finished culvert rehabilitation is shown in figure 3.

A10 Highway Culvert in Briis-sous-Forges

The second project was the rehabilitation of a culvert under the A10 highway in Briis-sous-Forges, France, which was carried out as a pilot project in 2019 by the highway owner (Ministère Chargé des Transports [France Ministry of Transportation] 2019; Huynh, Petit and Derimay 2019).

Figure 2. Photo. Spraying UHPC on the interior of the RCEA culvert (Huynh, Pettit, and Derimay 2019).

Figure 3. Photo. Interior view of the rehabilitated RCEA culvert (Huynh, Pettit, and Derimay 2019).

The interior of the culvert is 154.5 ft long, 12.1 ft wide, and 10.5 ft high. The culvert needed rehabilitation due to the significant amount of highway traffic on the road above it combined with a shallow fill of only 4 ft over the culvert. The project added a layer of UHPC on the interior face of the corrugated steel culvert that was designed to support all the dead and live loads independent of the original steel structure. Figure 4 shows the UHPC being sprayed onto the inside of the culvert. The sprayed UHPC had an average thickness of 3.0 inches, being 1.8 inches thick at the peaks of the corrugations and 4.1 inches thick at the valleys, which greatly minimized the reduction in clearance compared with conventional solutions. Because the UHPC was sprayed, no formwork was required.

This project included some changes versus the prior RCEA highway culvert rehabilitation. The fiber volumetric dosage was increased from 2.0 to 2.5 percent, and the compressive strength of the UHPC was increased from 18.9 ksi to 22.8 ksi. In addition, the distance from the pump to the nozzle was increased to as much as 200 ft.

Figure 4. Photo. Spraying UHPC on the interior of the A10 culvert (Huynh, Pettit, and Derimay 2019).

Projects in Switzerland

Two road tunnel rehabilitation projects using sprayed UHPC have been completed in Switzerland to date, as discussed in the following subsections.

Tunnel de la Roche, Between Saint-Brais and Glovelier

The rock-bored Tunnel de la Roche, connecting the town of Saint-Brais, Switzerland, with the town of Glovelier, Switzerland, was rehabilitated and enlarged in 2021, exactly 200 yr after the tunnel was first constructed. Trucks were getting stuck in the 40-ft-long tunnel about once per week, on average, so the project increased the tunnel width from 19.6 ft to 23.6 ft and increased the height at the crown from 15.7 ft to 18 ft (Holcim 2022; RFJ 2021; République et Canton du Jura 2021). The contractors chose sprayed UHPC to line the widened tunnel because of its strength and its resistance to water infiltration. This choice minimized the amount of rock that needed to be removed and reduced the construction duration. After installation of the UHPC, the contractors finished the tunnel walls with a 1.2-inch layer of conventional shotcrete, a 5/32-inch layer of sprayed waterproofing, and finally a 4-inch layer of conventional fiber-reinforced shotcrete. Figure 5 shows the Tunnel de la Roche before and after rehabilitation.

Figure 5. Photos. Tunnel de la Roche before after rehabilitation (Donzé 2021, 2022).

A. Before rehabilitation.

B. After rehabilitation.

Figure 6. Photo. T5 tunnel rehabilitation construction.

T5 Tunnel, Frinvillier

Also in 2021, the roughly 400-ft-long T5 tunnel on the N16 road just uphill from the town of Frinvillier, Switzerland, was rehabilitated through the use of 130 yd^3 of sprayed UHPC (Marti Arc Jura 2021). One reason the rehabilitation was needed was because the region contained an abundance of springs and creeks, whose water, over time, infiltrated the reinforced concrete tunnel lining, causing it to deteriorate (Péry La Heutte n.d.). The contractors replaced the tunnel lining with UHPC that was pumped into place in 16.4-ft-long sections, with a thickness between 3 inches and 4 inches. To reduce the likelihood of water infiltration at the connections between the 16.4-ft-long panel sections, the contractors excavated a 3.3-ft-wide annular band in the substrate at each panel connection location and filled it with UHPC before the installation of the pumped UHPC panel sections. Initially, the contractor formed and poured the first annular bands of UHPC at the connections, but after doing some trials with spraying UHPC, the contractor switched to spraying the UHPC bands to save time. The contractor subsequently used sprayed UHPC for the majority of the subsurface annular bands at the connections, as shown in figure 6.[4]

Projects in the United States

At the time of writing, no commercial construction projects have been completed using sprayed UHPC in the United States. However, at least two U.S. companies have completed trials of sprayed UHPC. Some transportation agencies are also beginning to consider the use of sprayed UHPC because of its many benefits.

UHPC Shotcrete Trial

In 2019, a U.S. contractor conducted trials of spraying UHPC on a natural rock wall, shown in figure 7, and on an inclined wooden surface. The contractor used a commercial UHPC product from Europe that was specifically modified for spraying with conventional concrete pumps. Although the pump deposited the UHPC faster than desired, the trial was still considered a success.[5]

[4]Ibid.

[5]Ibid.

Figure 7. Photo. Trial in 2019 of UHPC shotcrete in the United States.

Iowa State University Research Project

In 2022, Iowa State University, in collaboration with the California Department of Transportation, successfully pumped and sprayed UHPC to fabricate a full-scale pile cap shell and a full-scale column shell (Hays 2022). The researchers used a commercial UHPC supplier's standard UHPC mix pumped with the supplier's custom-designed equipment incorporating squeeze-pump technology (Kulish and McDonagh 2022). The UHPC was pumped on the top of the pile cap form and was sprayed on the sides of the pile cap form and on the column form. The UHPC deposition is shown in figure 8.

The researchers selected sprayed UHPC for the precast shell prototypes to demonstrate how they can be rapidly fabricated either on a construction site or at a plant. Then, because of their light weight, the precast shells can be easily transported and set into place with small equipment, where they will then be filled with conventional concrete. Hence, the durability benefits of UHPC can be applied to new pile caps and columns in a cost-effective and timely manner.

Figure 8. Photo. UHPC sprayed on column form at Iowa State University in 2022 (Hays 2022).

CONCLUDING REMARKS

Sprayed UHPC is emerging as a valid construction method in Europe for rehabilitating culverts, and infrastructure owners are considering additional rehabilitation projects on tunnels and dams. Sprayed UHPC combines all the advantages of UHPC, including its exceptionally high strength and durability, with a cost-effective and rapid installation process that eliminates the constraints of formwork and gravity. These constraints have previously limited where and how UHPC can be placed cost-effectively. These advantages can also be applied to other infrastructure applications, such as rehabilitating abutments and retaining walls, columns and piers, bridge deck soffits, and much more. Furthermore, as the Iowa State University research project demonstrated, sprayed UHPC can be a simple method to provide the durability benefits of UHPC to new construction. This benefit can be accomplished by making precast UHPC shells filled with conventional concrete, or by spraying UHPC on newly cast conventional concrete elements.

At least two commercial companies in the United States have performed successful trials of sprayed UHPC, and at least one U.S. company has designed and fabricated custom-integrated machinery for mixing, pumping, and spraying UHPC. Combined with the successes and lessons garnered from Europe's experience, this technology has a solid foundation. Sprayed UHPC has emerged as a preservation and repair solution, ready to be used by infrastructure owners wishing to take advantage of its numerous benefits.

ACKNOWLEDGMENTS

The original illustration in figure 1 is the copyrighted property of Freyssinet and Holcim and can be accessed at https://www.iastatedigitalpress.com/uhpc/article/9725/galley/9846/view/ (Doiron 2019). The original illustration was modified to eliminate metric units, change how U.S. standard units are displayed, replace "ductal" with "UHPC," replace "Concrete culvert axis" with "Culvert axis," and eliminate extraneous content on the left side of the cross-section view.

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