A UHPC OVERLAY FOR DETERIORATED BRIDGE DECKS

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Abstract

Deterioration of existing bridge decks, which usually originates with deck cracking on the top surface, is a common problem in North America. It causes frequent repair of the decks to limit further damage resulting from water/chloride ingress. Due to the superior engineering and durability properties, use of an ultra-high performance concrete (UHPC or UHPFRC) deck overlay is an attractive alternative to minimize damage to bridges. Recently developed UHPC thixotropic mix designs enable UHPC overlay to be used on decks with slope and meet specific crowning requirements. The use of this UHPC with 3.25% of steel fibers was successfully evaluated under laboratory conditions. The feasibility of applying this technology in the field was then investigated on a small bridge for the first time in North America in May 2016. This paper presents the details about the laboratory evaluation, field implementation of UHPC overlay, and lessons learned from this first UHPC overlay project in North America.

Résumé

La détérioration des tabliers de ponts existants, qui provient habituellement de la fissuration du pont en surface de l'extrados, est un problème habituel en Amérique du Nord. Cela occasionne des réparations fréquentes du tablier pour limiter les dommages ultérieurs causés par l'infiltration d'eau ou de chlorures. Avec ses propriétés constructives et de durabilité supérieures, l'utilisation d'un revêtement en béton à ultra-hautes performances (BFUP) est une option intéressante pour minimiser les dommages que subissent les ponts. Récemment développées, des formules de BFUP thixotropes permettent de mettre en œuvre le revêtement sur des tabliers avec des pentes et de répondre à des exigences de surface spécifiques. L'utilisation d'un tel BFUP comprenant 3.25 % de fibres d'acier a été évaluée avec succès dans des conditions de laboratoire. La faisabilité de l'application de cette technologie sur site a été investiguée sur un petit pont pour la première fois en Amérique du Nord en mai 2016. Cet article présente les détails de l'évaluation en laboratoire, de la mise en œuvre du revêtement BFUP in-situ, ainsi que les leçons tirées de ce premier projet de revêtement en BFUP en Amérique du Nord.

1. INTRODUCTION

Bridge deck deterioration is a frequent problem faced by many states in the U.S., especially the Northern states where deicing is used and Coastal states. Maintenance and repair associated with bridge decks can cost 50 to 80% of all bridge related expenditures, which is conservatively estimated to be more than $5B per year [1]. Typical bridge deck deteriorations include cracking, spalling, delamination, and corrosion of reinforcement. Various phenomena contribute to deck deterioration, including poor initial quality, the use of deicing salts in winter, overloading, stresses associated with freeze-thaw cycles, fatigue, corrosion of reinforcement, or any combination thereof. Near the coast, the bridge decks can experience damage due to seawater salt. Several of these problems initiate due to surface cracking and infiltration of moisture and chloride into the deck.

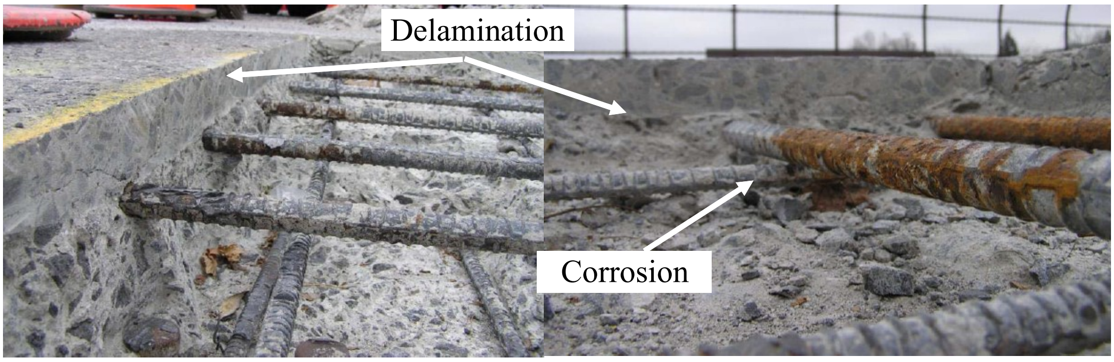

Figure 1: Examples of damage to bridge deck [1]

A variety of techniques are used to repair damaged bridge decks. They can range from grouting to seal surface cracks to partial/full depth patching to replacing partial/full bridge deck. While each of these techniques can increase the service life of the bridge decks, none has been proven to completely prevent further bridge deck deterioration nor do they increase the longevity of bridge deck.

With its superior durability properties, the use of ultra-high performance concrete with fiber reinforcement (UHPC or UHPFRC) in bridge deck has been explored in Iowa as a means to combat the wide-ranging bridge deck deterioration problems. Given that solid UHPC slab deck is prohibitively expensive, use of waffle deck was successfully demonstrated [2] [3]. To further reduce the construction cost and broaden the application of UHPC in bridge decks, use of a thin UHPC layer as an overlay was then explored with an intention of preventing deck cracking, reducing fatigue damage and minimizing penetration of moisture and chloride ion into the bridge deck. To ensure cost effectiveness of this concept, the thickness of UHPC layer was targeted to be less than 50 mm with no mechanical connection between the UHPC layer and underlying normal concrete (NC) deck. A systematic investigation involving slant shear tests and flexure and shear tests on 2.74 m (long) x 0.81 m (wide) concrete deck concluded the following [4]:

- A thin UHPC layer as an overlay has the potential to increase longevity of bridge deck;
- To ensure composite action between UHPC and NC, a minimum interface roughness of 3 mm is required;
- A modified UHPC mix is needed to ensure that UHPC can be placed on sloped surfaces and allow necessary crowning to be done in the field; and

- A field evaluation of UHPC overlay is necessary to ensure the surface or interface is affected by freeze/thaw cycles and fatigue loading.

Focused on increasing both the strength and durability, UHPC-NC composites were explored in Switzerland [5]. To enhance the strength of the composite slab, mild steel reinforcement is placed within the UHPC layer and this reinforcement mat is intended to be tied to the NC slab using vertical bars penetrating into the slab. This research led to field applications and development of a standard. The largest application of this effort was the rehabilitation of bridge decks of the Chillon Viaducts near Lausanne, Switzerland. Completed in 1969, the viaducts consist of two 2.12 km long concrete box-girder bridges and required refurbishment of 52,000 m^2 surface area. This project was completed in 2015 by WALO, who developed a special placing and batching equipment that could sustain the large volumes of UHPC (capacity of 9 m^3 per hour) required for the job. LarfargeHolcim's provided a UHPC mix with 3.25% steel fiber content for this project, in which an overlay thickness ranging from 40 to 50 mm was used.

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Figure 2: Chillon Viaducts and placing of UHPC on bridge deck

As a guide for the design and specification of UHPC overlays, SIA 2052 [6] has recommended the appropriate mix based on the type of application. For UHPC Class UA or UB, the possible application of overlay is depicted in Figure 3. These two UHPC classes require strain-hardening characteristics with an ability to withstand the development of eigenstresses due to restrained shrinkage, without cracking, a minimum bond stress of 1.5 MPa, and a rheology compatible with the ability to place UHPC at a slope of up to 10%.

2. ESTABLISHING AN OVERLAY MIX

2.1 UHPC mix consistency

A beneficial characteristic of UHPC is its ability to flow and self-level, which has been taken advantage of in previous projects completed in Iowa [7]. Using the same type of consistency on a bridge deck would be challenging because most decks have slopes and cross-slopes. Therefore, LafargeHolcim worked on a new UHPC overlay formulation that can maintain a slope of up to 7% when placed on bridge decks. This formulation, which was comparable to the mix used on the Chillon viaducts, used components available in the U.S. and included 3.25% of steel fibers. These fibers were 0.2 mm in diameter and 13 mm in length.

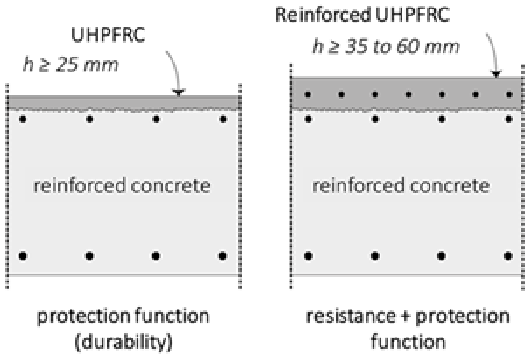
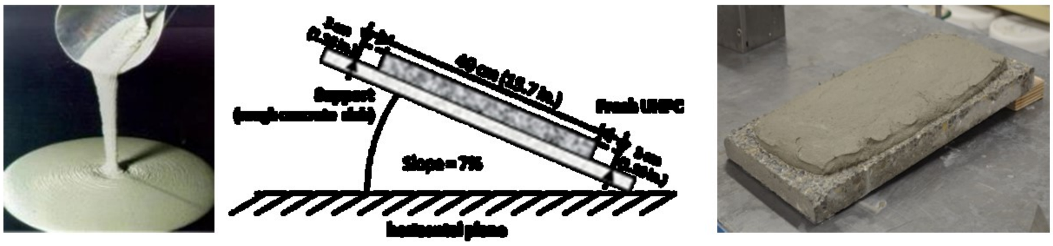


Figure 3: SIA 2052 recommendations for UHPC overlay (MCS-EPFL 2016)

Standard slump or flow tests are not useful for a UHPC overlay mix because of its stiff rheology. A method to verify that the mix can hold a required slope is suggested in SIA 2052. By using a platform to replicate the slope of the bridge deck under consideration, the UHPC formulation can be adjusted for that specific slope (see Figure 4). The goal here is to use a formulation that is as flowable as possible to facilitate placing, while the mix also needs to hold the specified slope. By testing the material after batching, if it is found that the consistency requires an adjustment, this can be done before the material is used on the deck.



a) Flow test **b) Slope test dimensions** **c) Slope test of a UHPC mix**

Figure 4: Testing of UHPC rheology

2.2 Strain Hardening

Critical characteristics of the overlay mix include impermeable surface and strain hardening, which typically requires steel fibers. Steel fibers are costly and using them efficiently in a mix is important. Therefore, the amount of steel fibers used in the mix needs to be sufficient to allow stresses to be taken by the steel fibers without cracking the mineral matrix. Testing conducted by LarfargeHolcim suggested that 3.25% of steel fibers per volume would be optimal for the overlay application. The basic characteristics of this UHPC overlay mix as produced by LafargeHolcim are summarized in Table 1.

3. LABORATORY TRIAL

To verify the quality of the UHPC overlay mix and provide an opportunity for a contractor to experiment the mix, two 2.4 x 2.4 m^2 square slabs were cast with typical deck reinforcement details. They both were 197 mm thick; one of the surfaces was finished with exposed aggregates and the other was constructed with a broom-finished surface (Figures 5a and 5b). Both slabs were positioned at 6 degrees of slope and UHPC overlay mix was batched and placed on the slabs at the structural engineering laboratory at Iowa State University (Figure 5c). This exercise confirmed that the selected UHPC overlay mix is satisfactory in terms of ensuring workability and holding the slope when placed on a roughened surface.

Table 1: Basic properties of the UHPC overlay mix

Property	Typical Value
Uniaxial tensile behavior: type	UA per
Elastic tensile strength	8.0 MPa
Tensile strength	9.0 MPa
Strain when the tensile strength is reached (hardening)	0.35 %
Compressive strength on cube	125 MPa
Modulus of elasticity	45 GPa
Total shrinkage at 90 days	0.7%
Water porosity at 90 days	6%
Apparent gas permeability at 90 days	$\leq 0.5.10^{-19}$ m^2
Diffusion coefficient of chloride ions at 90 days	$\leq 0.5.10^{-12}$ m^2.s^{-1}

*commercially available version of the product is Ductal® NaG3 TX

Figure 5: UHPC overlay trial in the laboratory: a) surface with exposed aggregates; b) broom-finished surface; c) placing of UHPC on one of the slabs

4. PROTOTYPE BRIDGE

After evaluating several candidate structures, the three-span, two-lane, Mud Creek Bridge located on Buchanan county road D48 near Brandon, Iowa, was selected to experiment the first UHPC overlay on a bridge deck in North America. This 30.5 m long and 8.5 m wide straight continuous concrete slab bridge has a 5% superelevation and was built in the mid-1960s. An aerial view and condition of the bridge deck surface prior to applying the UHPC overlay are shown in Figure 6.

a) Aerial view (*curtesy of Google*)

b) Condition of bridge deck

Figure 6: Mud Creek Bridge in Buchannan County, Iowa.

5. FIELD APPLICATION

The UHPC overlay was applied to the deck surface of the Mud Creek bridge in May 2016. A key driver for bridge overlay applications is the speed of the intervention. Traffic needs to be returned to the bridge in the shortest time possible. In this particular case the targeted duration of two weeks was accomplished from closure to opening of the bridge for public use.

As the first step following the closure of the bridge, the top 6 mm of the deck surface was removed. To ensure a satisfactory surface roughness, the deck was then grooved along the bridge length, leaving a surface roughness with an amplitude ranging from 2 to 3 mm. Finally, the deck was thoroughly cleaned and adequately saturated with water before placing the UHPC overlay.

5.1 On site batching and placing

For bridge projects in the U. S., batching of UHPC is typically performed on site by the contractor. Normally, small amounts of material are required and placing takes time, and hence batching output is normally not the main driving factor. For large overlay jobs, having a portable batching plant on site as demonstrated for the Chillon Viaducts project will be beneficial. However, for small to medium span bridges such as the Mud Creek bridge, using large size portable mixers was considered sufficient. For this first overlay project, a pair of high shear pan mixers were used. Each mixer had the capacity to take a bulk bag of UHPC premix, yielding approximately 0.5 m^3 of material per batch. The typical duration of loading and batching of the UHPC took approximately 20 minutes. The UHPC overlay mixing was done at one end of the bridge and transported to the working area using a mini concrete dumper.

To place the UHPC efficiently, the deck was divided into two regions along the longitudinal axis of the bridge and the overlay was placed separately for each lane on two different days without using any special detailing across the construction joint. After the UHPC overlay mix was spread on the surface, a vibratory truss screed was used to compact the UHPC and maintain an overlay thickness of 38 mm. A local contractor, who executed the project, had no prior experience with UHPC, and thus experimented with placing of the UHPC overlay material on a flat ground surface prior to working on the deck. Although placing of the UHPC overlay on the first lane took longer, the contractor successfully placed all the material on the second lane within 3 to 4 hours. This included some wait time for the batching of the UHPC. A series of pictures from the construction site is shown in Figure 7.

Figure 7: UHPC overlay on Mud Creek bridge deck: a) trial run; b) placing of UHPC on the deck surface; c) Lane 1 after placing UHPC; d) construction joint after grinding part of the deck; e) grooving of the surface; f) finished surface

5.2. Curing

Hardening of UHPC normally takes a fair amount of time and is highly depended on ambient temperature conditions. Using accelerators and heating are two alternatives that can help speed up the process. However, both of these options are not ideal for an overlay application. Heating is not practical for large surfaces and using an accelerator would make batching and placing challenging. Therefore, both options were not used for the bridge deck overlay project. In North America, when UHPC has been used for joint closure pours applications, traffic is usually allowed back on the structure as soon as the UHPC gains a strength of 80 MPa. A similar approach was adopted for the UHPC overlay project. The compressive strength of the overlay mix was evaluated after two and three days, and the average measured values were 65 MPa and 85 MPa, respectively. Therefore, grinding and grooving of the UHPC deck surface was permitted after 3 to 4 days.

6. LESSONS LEARNED

From concept development through installation, all parties involved in this first UHPC overlay application in North America put forward their best efforts and the result was a very successful project. Once a suitable bridge was identified, securing funding and coordinating with local contractors had some challenges because of the unfamiliarity with UHPC. Batching of the material on site using two portable mixers was satisfactory. However, the process could be optimized. A trained, sufficiently large crew to work with the mixers is important. Speeding up the batching by any means, for example by introducing the steel fibres more quickly in the mix, would be helpful. For larger project, the use of a portable batching plant or delivery of the batched overlay material would be more appropriate. The consistency of the material was such that it was difficult to move it around manually with racks and shovels as typically done with concrete overlays. This was demanding on the construction crew and thus more people were required to work with the material in front of the screed. Lightly misting the UHPC in front of the vibrating screed seemed to help with the consolidation of the layer and prevented the material from sticking as much to the vibrating ruler. Nonetheless, the crew placing and screeding the surface was about twice that required for a normal overlay job.

One of the goals of the project was to place the UHPC overlay with basic concreting equipment and the local contractor accomplished this goal using a simple vibrating screed machine and establishing a manual cranking setup to move the screed along the length of the bridge. While this process was satisfactory and cost effective, a specially designed equipment for placing the UHPC overlay may be appropriate to place the material efficiently and provide higher quality finish surface. It was felt that the ruler of the screed used for Mud Creek bridge project was not vibrating enough, making the top surface not very smooth. This required grinding of the surface prior to grooving.

The use of a curing compound was extremely important to keep the moisture within the UHPC layer immediately after consolidation by the screed machine. Determining the optimal curing time before grinding will need to be studied going forward so that this step can be completed cost effectively. Although 80 MPa was used as a threshold value for allowing the grinding to take place, it was felt that this threshold value is conservative and a lower value may be appropriate, which will reduce the duration of the project and grind the surface more cost effectively. Grinding and grooving the surface on this project required relatively more effort because the UHPC was stronger and harder than a conventional overlay, but these steps were successfully carried out by a local contractor.

There was no special consideration given to the cold joint between the two overlay passes. A simple vertical joint was used. To ensure proper waterproof of this joint, a key and/or a textured surface and even the use of short rebar may be needed to avoid water penetration in the long term. With further investigation over a period of years, the applicability of a simple vertical joint along the bridge length needs to be confirmed. While more intricate joint details may be more suitable, it will increase the cost of the overlay installation. Finally, the operating of the UHPC mixers required three-phase power supply at the project site to operate the mixers and the cost of this should be integrated into the contract upfront.

7. CONCLUSIONS

This paper has presented a summary of steps taken to utilize UHPC as an overlay material for bridge deck surfaces in order to minimize the maintenance and repair costs of bridge decks in the U.S. Several steps were taken to: a) establish a suitable UHPC mix formulation that was never used before in North America; b) verify its application under laboratory condition; and c) demonstrate the placing of the material on an actual bridge deck.

All of the goals set out for this overlay project were successfully accomplished, which included the use of a local contractor, with no prior UHPC experience, to complete this small overlay project using basic concreting equipment and local manpower. The contractor used a larger crew than that required for a typical concrete overlay project and installed the UHPC overlay with a basic vibrating screed machine. Despite the success of this project, several improvements to the installation process have been identified. They include use of a small special equipment to place, vibrate and even grove the surface when placing the UHPC, thereby increasing the efficiency of batching the UHPC on site and reducing the construction time.

The results from laboratory investigation were used as a guide to determine the surface roughness and thickness of the overlay. However, a long-term monitoring of the Mud Creek bridge deck would be critical to ensure that the UHPC overlay would increase the longevity of the bridge deck and reduce the maintenance cost. The project will also be monitored and will become a very useful reference to evaluate its performance. It is commonly believed that a UHPC overlay will be much more durable compared to various other overlay concepts used today. However, more quantifiable benefits of the UHPC overlay are required to ensure that widespread application of the new technology would be economical and that it will help combat the widespread bridge deterioration problems facing the nation.

A 40 mm UHPC overlay is ideal as a running impermeable surface for a bridge deck. However, a UHPC layer in conjunction with a rebar mat can also be used to increase the deck capacity. Such a system could be used instead of performing full deck replacement. Using the remaining capacity of an existing deck and providing a top impermeable, durable UHPC surface would allow faster construction and be more sustainable than demolishing an existing deck and casting of a completely new deck. This would take full advantage of UHPC as a high performance material to build better system.

The Iowa overlay project findings will be used to assist other jurisdictions across North America to develop specifications that can be adapted to their needs.

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