ULTRA HIGH PERFORMANCE SHOTCRETE: YES WE CAN!

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Abstract

There is nowadays a growing need for durable repair and retrofitting techniques, for tunnels, culverts, port infrastructures etc. Actually UHPFRC is ideal, given its superior mechanical and durability properties. However, up to now this material was only applied by conventional gravity casting. However, when the surfaces are vertical and/or complex, the casting of thin layers against existing old concrete is not an easy task. To fit this need, LafargeHolcim is developing sprayed UHPFRC. From a mix-design perspective, the novelty lies in the fresh state behavior of the fresh mix: a high yield stress combined with a moderate plastic viscosity. It should be outlined that this unusual fresh behavior does not affect the hardened concrete properties. Tests will be presented, in which the material is pumped and sprayed by the wet process. The fiber orientation is investigated through tomography and flexural tests in several directions. Mechanical properties and durability results are shown.

Résumé

Le besoin de techniques de réparation durables pour les ouvrages tels que les buses, les tunnels, les infrastructures de ports… est de plus en plus important. Le BFUP est réellement une solution idéale au regard de la supériorité de ses propriétés mécaniques et de sa durabilité. Jusqu'à maintenant, ce matériau a essentiellement été appliqué par coulage gravitaire. Cependant, quand les surfaces sont verticales et/ou complexes, la mise en œuvre de fines couches de BFUP sur un support de béton ancien n'est pas une tâche aisée. Pour répondre à ce besoin, LafargeHolcim développe le BFUP projeté. D'un point de vue formulation, l'innovation repose sur le comportement rhéologique du mélange frais : un seuil significatif combiné à une viscosité plastique modérée. Il faut souligner que cette rhéologie, inhabituelle pour les BFUP, n'affecte pas les propriétés du béton durci. Les essais de pompage et projection sont décrits. L'orientation des fibres est étudiée par tomographie et grâce à des essais de flexion dans différentes directions. Des résultats de caractérisation mécanique et de durabilité sont présentés.

1. INTRODUCTION

Since their first appearance in the early nineties, the mix-design of UHPFRC has led most of the time to self-leveling rheological behavior (optimization of the granular skeleton, very small amount of water…). Consequently, the targeted applications had to be compatible either with horizontal placing, or required adapted and often costly formworks. For some applications, in particular in the domain of retrofitting, even the use of formwork can become a real challenge (much reduced working area, complex shape of the support …) or even unrealistic from a technical and/or economical point of view.

Wet-mix shotcreting of UHPFRC represents an interesting alternative to tackle the above-mentioned difficulties which enables keeping the undeniable advantages of UHPFRC in terms of mechanical properties and durability. However, the technical stakes are high. Indeed concrete/process interactions involved with such a way of using this new type of UHPC have not yet been studied. The path that was chosen here is different from the one studied by Vollmann *et al.* [2]. Instead of accelerating a self-leveling UHPC, the idea (and the technical challenge) is to realize a mix-design of UHPC with a specifically fine-tuned fresh state behavior which allows shotcreting without any use of redundant admixtures while maintaining mechanical and durability performances required for UHPFRC. Based on the current experiences from various Ductal® applications [3], we defined the targeted fresh state behavior described in Figure 1.

A new strategy of mix-design enables to use UHPFRC in vertical applications (or even in vaults) without additional admixtures at the level of the nozzle. However, consequences of this new way of placing had to be assessed. In this paper, the main interest is focused on the assessment of the final mechanical properties and durability. Furthermore, specific tests as absorption of energy were executed. This article describes the wet-mix shotcrete of Ductal® done in LafargeHolcim R&D facility as well as the characterization of the hardened product.

2. EXPERIMENTAL PROGRAM

2.1 Fresh state behaviour

The mix-design of UHPFRC was significantly revised as the rheological targets were very far from the ones currently used in the domain of self-leveling UHPC. The yield stress is defined as the stress level necessary to make a fluid or a suspension flow. Self-leveling materials have typically a low yield stress which facilitates the pumping [1]. However, in the case of shotcreting, the product should have a significant yield stress as soon as the mixing phase is done in order to shotcrete it without using any accelerator. Furthermore, the viscosity should remain at a reasonable level so that the product can be pumped on long distances. Therefore, the main challenge was to find the good compromise between an acceptable viscosity and a sufficient yield stress preventing the flow of the sprayed product along the substrate material.

Figure 1 describes the fresh state behavior that enables to meet these specifications.

- High enough yield stress > 300 Pa considered at a shear rate of $0.07s^{-1}$
- Relatively low viscosity: 20 à 40 Pa.s at a shear rate of $15s^{-1}$.

These values were defined with a rheometer Anton Paar MCR301. Moreover, the incorporation of a high dosage of metallic microfibers could cause blocking of the product during the pumping phase and had to be considered.

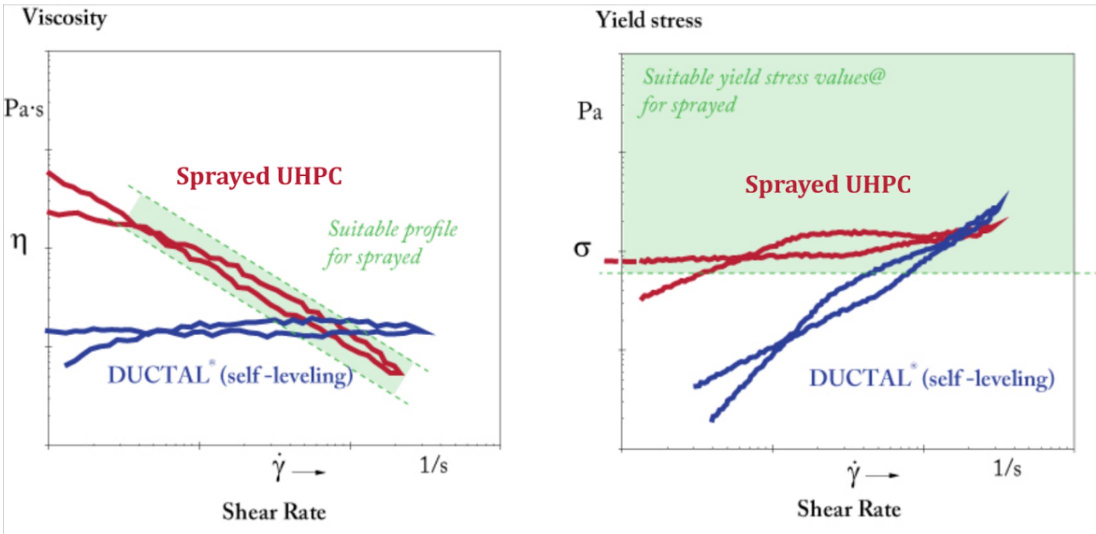


Figure 1: Fresh state behavior comparison between a self-compacting Ductal® and a sprayed Ductal®

2.2 Raw materials, Mix design and Mixing

The raw materials were conditioned as a pre-blended mix including cement, cementitious, additives and sand (D_{max} < 1mm). In order to reach the targeted rheological compromise between ability to be pumped and capability to stick to the vertical support, proportions of cement, cementitious, additives and sand were optimized to create the adapted skeleton. The dosage of steel fibers (Ø 0.2/13mm) varied in order to take into account various applications.

After the solid phase optimization, water and admixtures quantities had to be adjusted to reach the rheological targets. The search of a viscosity compatible with the pumpability in 50mm diameter pipes on distances of 50 meters and more couldn't be done with excessive water additions. Indeed, the performance indicators mentioned in the NF P 18 470 standard have to be warranted, even if the solution is not yet covered by this standard. The mixing of the premix was done at the experimental concrete plant available at LafargeHolcim R&D center. The UHPC was produced with a vertical axis mixer, by batches of 400 liters. At the end of the mixing, the product was carried and discharged into the tank of the pump.

2.3 Pumping equipment

The equipment used for this experimental program was a current piston pump. This pump works with two parallel pistons having a double stroke (back and forward). Pistons in both cylinders work in opposite direction. The pistons are driven by hydraulic cylinders. When the piston goes backward, it is filled with the concrete, when it goes forward it pushes the concrete in the pipe. A valve enables to change concrete cylinder so that the cylinder filled with concrete is connected to the pipe. The product was pumped through 50 mm diameter flexible conducts. This reduced diameter enables manual shotcreting. The rheology of this type of UHPC during pumping is under study in a more extensive way in order to give a description or even a modelling of the behaviour in the pipe (level of friction, existence of a lubricating layer…).

2.4 Shotcrete equipment

The product was sprayed by wet-mix shotcrete process. The mixture was projected onto the support (concrete sandblasted wall or boxes) by using compressed air (Figure 2). At the level of the nozzle (Figure 3), two conducts currently arrived: one for accelerator, the other for air. In our case both are used for air feeding.

Figure 2a) Manual UHPC sprayed on a sandblasted concrete wall (60 mm thickness);
2b) UHPC sprayed by robot

Figure 3a) Manual UHPC spraying in boxes for producing plates for mechanical and durability tests; 3b) Wet-mix nozzle with 45 mm exit diameter

Table 1 Specimens for mechanical and durability tests

Tests	**Standards**	**Samples**	**Number of samples**
Compression tests	NF EN 14 488-2	Cores ø 60 x 120 mm	12
4 points flexural tests	NF P 18 470	70x70x280 mm	3
3 points flexural tests	NF P 18 470	70x70x280 mm	6
Absorption of energy EN	NF EN 14 488-5	600x600x100 mm	5
Absorption of energy adapted to UHPC	NF EN 14 488-5	600x600x50 mm	5
Absorption of energy adapted to UHPC	NF EN 14 488-5	600x600x30 mm	5
Hydraulic abrasion	CNR Test	100x100x100 mm	3
Frezing-thawing tests	NF P 18 424	100x100x400 mm	3

After shotcreting, plates were covered with a polyethylene blanket in order to avoid early drying and stored outside. Twenty-four hours after shotcreting, UHPC plates were unmoulded, cut and drilled to produce the adequate samples for mechanical and durability tests. The specimens (Table 1) were stored in a humid chamber (20°C, 95% RH).

3. RESULTS AND DISCUSSION

3.1 Adjustment of the rheology

The rheology was assessed on the matrix, before adding metallic fibres, by using a rheometer with imposed constraint. The rheometer applies to the material a specified torque. By this measurement, shear stress and viscosity are obtained (Figure 4).

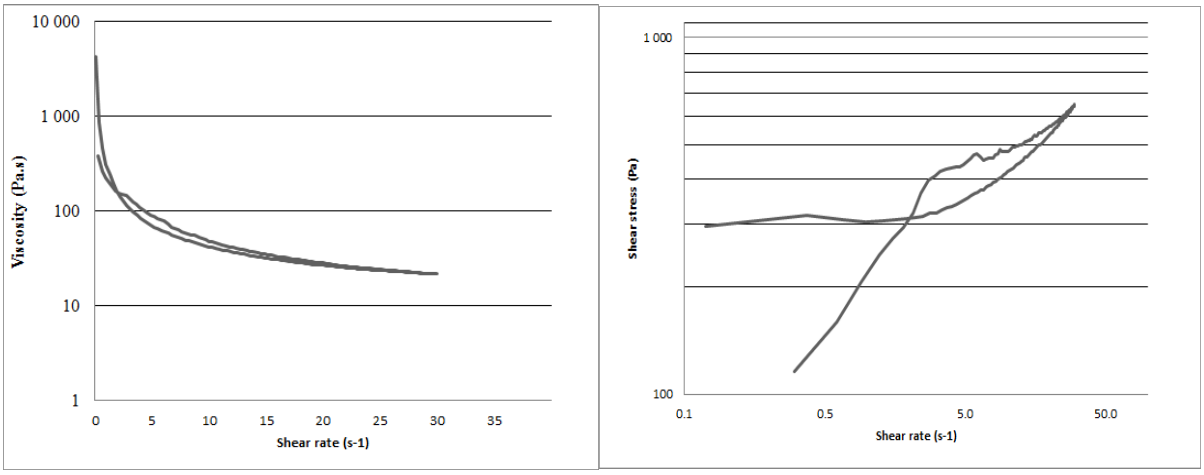


Figure 4 : Rheological profile of a sprayed UHPC

3.2 Rebound and orientation of fibres

3.2.1 Assessment of the rebound of fibers

In order to assess the actual quantity of fibres in the shotcrete UHPC (to validate the absence of specific rebound of fibres), a sample of around 1 litre of fresh product was taken from the wall just after spraying and washed on a 200 µm sieve. After washing, the fibres retained on the sieve were dried then weighted, to compare this quantity to the amount of fibres incorporated in the mixer. For both quantities of 2.0 and 3.3 % by volume, no specific loss was noted.

3.2.2 Assessment of the orientation of fibers

<u>*Mechanical tests*</u>

In order to assess if a preferential orientation of the fibers occurred in the plan parallel to the support, flexural test have been realized. Three specimens of 700 x 700 x 280 mm were cut in each of two orthogonal directions after placing by shotcrete in a box. The results (Figure 5) didn't show any difference between both directions. The fibers were randomly dispersed in this plan, giving isotropic reinforcement of the UHPC in place.

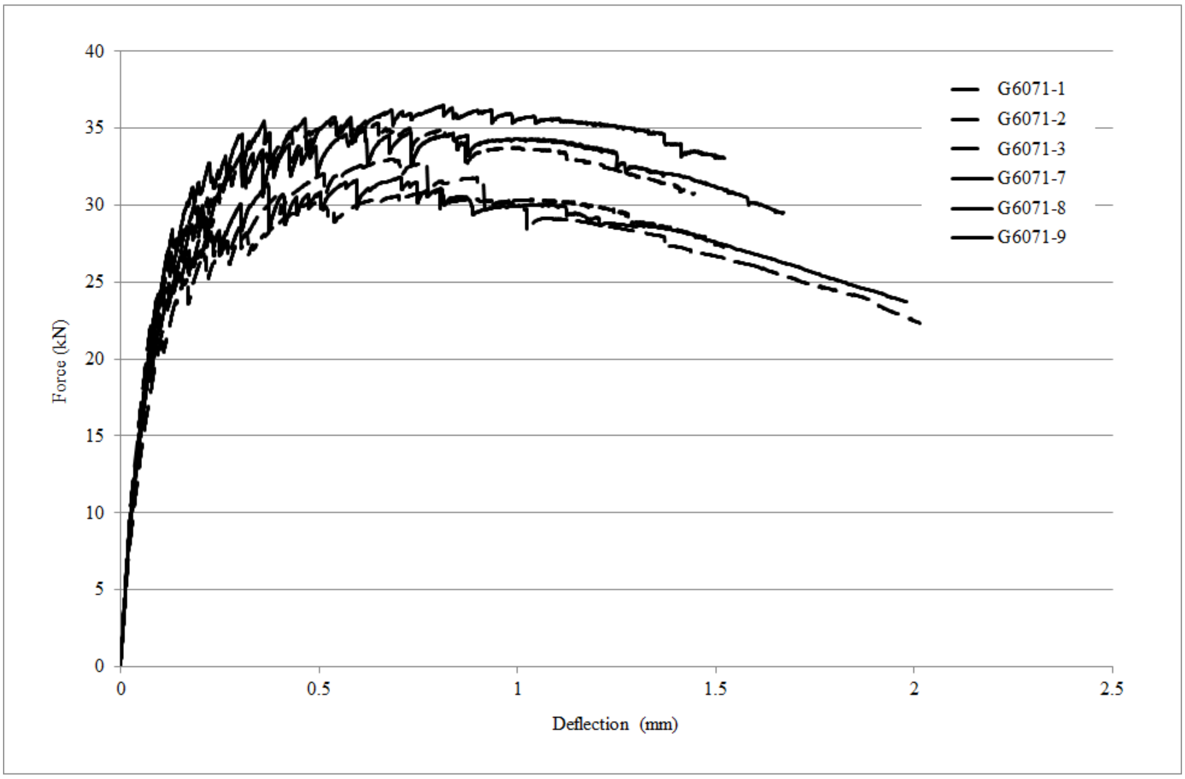


Figure 5: Three-point flexural results on samples cut in horizontal direction (3 - continuous line) and in vertical direction (3 – discontinuous line)

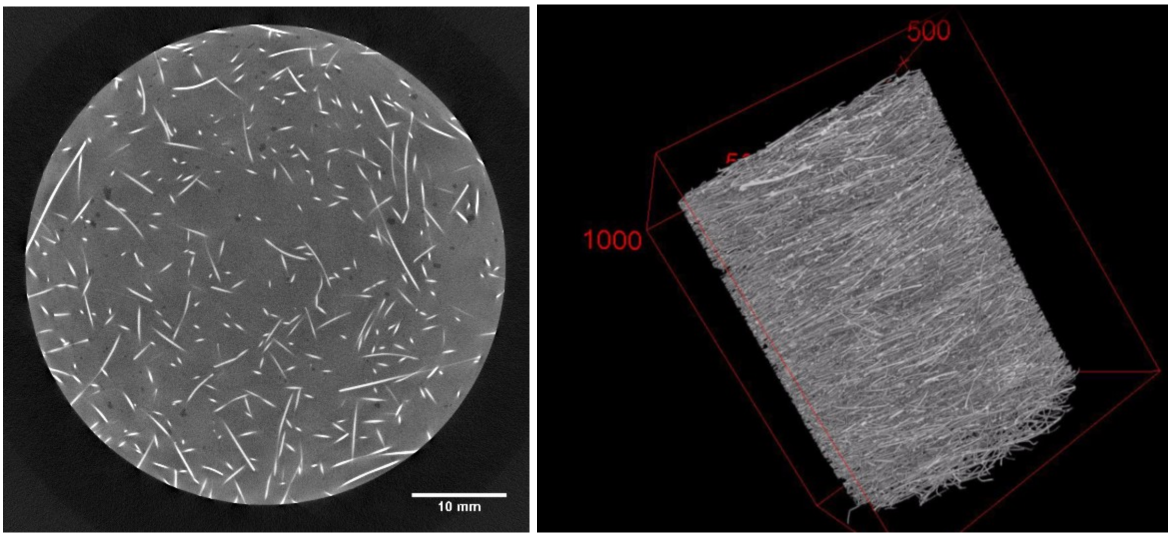


Figure 6a) 2D cross section in the (x,y) plan 6b) 3D tomographic reconstruction

Tomographic analysis

Cores of UHPC were drilled on the concrete support. (x,y) is the plan perpendicular to the projection direction; z axis is parallel to the projection direction. From figure 6a) we can observe that no preferential orientation of the fibres is visible. Figure 6b shows clearly the homogeneity of the fibres content from support to external surface and the very high number of micro-fibers.

3.3 Mechanical characterization

Compressive strength, flexural strength and energy absorption were measured respectively on 60 mm diameter cores (NF EN 14488-2), specimens of 700 x 700 x 280 mm (NF P 18 470) and 30, 50 and 100 mm thickness plates of 600 x 600 mm (adapted from NF EN 14488-5).

Compressive and flexural strengths

Table 2 shows the results of compressive strength; values in brackets are [min-max] obtained values. The strength gain between 7 and 28 days for the formula with 2 % of metallic fibers is below the gap expected and difficult to explain. We can see from Table 3 the high improvement of MOR (3 points flexural tests) brought by the additional content of fibres. The high capacity of load bearing of this UHPFRC is convenient for a large range of structural applications.

Table 2 : Compressive strengths on mix-designs with 2.0 % and 3.25 % of metallic fibers

	2% fibres	3.25% fibres
Air (%) Hydrostatic weight	**0.3**	**0.9**
Actual fibers content	**2.0%**	**3.25%**
Compressive strength		
CS 7d (Ø 60) MPa	**178 [174-183]**	**179 [173-185]**
STD	**4.4**	**5.9**
CS 28d (Ø 60) MPa	**181[178-182]**	**197[180-214]**

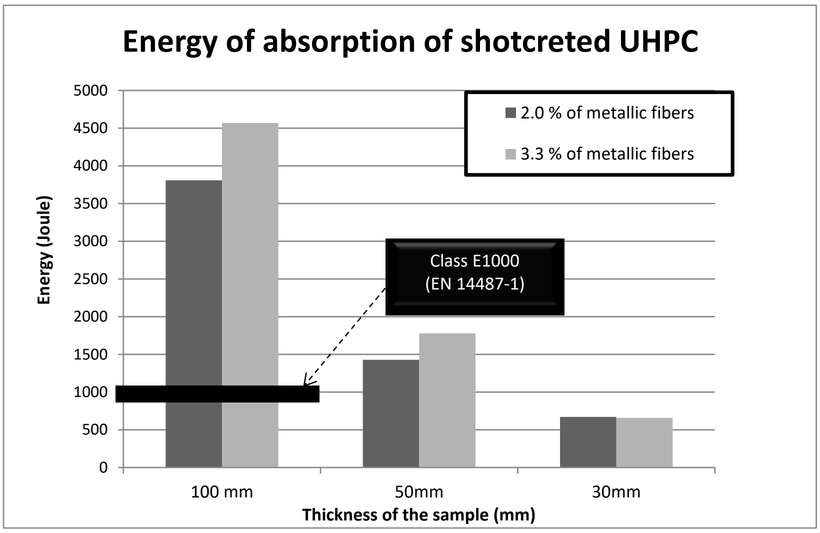
Table 3: Flexural strengths of mix-designs with 2.0 % and 3.25 % of metallic fibers

	2% fibres	3.25% fibres
3 Points FLexural strength		
MOR (28d) MPa	**27**	**34**
4 Points FLexural strength		
LOP (28d) MPa	**10.8**	**13.7**
MOR (28d) MPa	**25**	**29**

Absorption of energy

Absorption of energy is a test specific to shotcrete domain. The standard is adapted to current shotcrete concrete; therefore the specimen of test has a 100 mm thickness.

For UHPC applications, we presumed that the thicker layer of sprayed UHPC won't be higher than 60 mm most of times. During the test, the slab of 600 x 600 mm² was supported on the four sides. A central point load was applied through a contact surface of 100 × 100 mm², at a constant speed of 1 mm/min. A displacement sensor LVDT gives the deflection at the central point of the slab. The absorbed energy is represented by the area under the load-deflection curve. The value of energy absorption capacity (Figure 7) increased obviously with thickness and fibre content. 50 mm-thick samples gave energy of absorption higher than E1000 (higher specification in EN 14487-1). This thickness is relevant from a technical-economical point of view for numerous applications.



	Absorption of energy (Joules)	
Thickness of 10 cm	**3807**	**4572**
Thickness of 5cm	**1434**	**1776**
Thickness of : 3 cm	**669**	**662**

Figure 7: Results of absorption of energy (Joules)

3.4 Durability tests

The measurement by hydrostatic weighing has shown very low porosity of the samples (< 1.0%). This level of air content is the warrant of a very dense matrix that ensures high durability. Resistance to freezing and thawing test were realized (NF P 18 424). No alteration of the specimens was noted after the 300 cycles (assessed on resonance frequency, Figure 8). Values above 100 are due to the uncertainty of the method (standard deviation of 30 Hz). A concrete is stated “resistant to freeze-thaw tests” if $\left({F_n^2}/{F_0^2} \times 100 \right) < 75$.

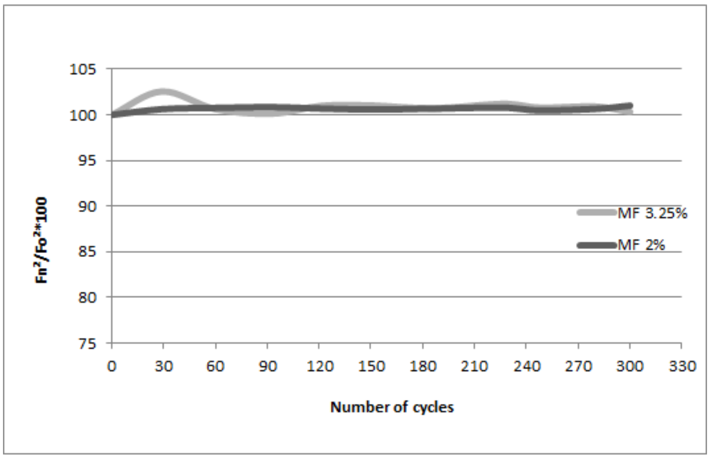


Figure 8: Evolution of resonance frequency during freeze-thaw tests

4. CONCLUSION

The tests described here demonstrate that despite the constraints on mix-design and fresh state behavior due to the shotcreting process, it was reachable to maintain high mechanical performances and excellent durability.

The first pilot is taking place in a few weeks in France. The objective is to repair a metallic culvert (covered channel that crosses under a road, railway, etc.) damaged by corrosion. A thin layer of Ductal® is sprayed on the internal surface of the culvert to create a new structure. In France, the solution is implemented by Freyssinet.

Finally, this new technique opens a wide range of new applications, increasing the potential share of Ductal® shotcrete among the range of civil engineering applications and allowing a unique lifespan extension tool for many aged facilities.

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