

STRENGTHENING OF HYDRAULIC STRUCTURES WITH UHPC

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Abstract

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) provides excellent durability qualities and performs well in hydraulic structures that are exposed to extreme environments and require resistance to impact and abrasion. The following UHPFRC projects are detailed:

- the Caderousse and Beaucaire Dams on the Rhone River, France, operated by Compagnie Nationale du Rhône (CNR): UHPFRC from Lafarge was used to repair the foundation slab of a gate bay as well as vertical walls;
- Channel-bridges over the Maurienne motorway (Alps, France): Aluminous concrete was replaced with about 648 m² of UHPFRC from Vicat and Eiffage on a 10 % slope slab;
- the 'Les Bois' hydroelectric power plant in Chamonix (Alps, France), operated by Electricité de France: UHPFRC from Eiffage and Lafarge was applied between rails in the underground water intake. The water arrives directly from the glacier river of the 'Mer de Glace' and is extremely abrasive.

Each of the above projects is regularly exposed to severe environmental conditions and demonstrates that UHPFRC provides innovative solutions for hydraulic structures.

Résumé

Les bétons fibrés à ultra-hautes performances (BFUP) présentent des qualités de durabilité et de résistance dans des conditions extrêmes très recherchées pour des ouvrages hydrauliques, soumis à des impacts et de l'abrasion. Leur utilisation dans des conditions sévères est présentée sur trois exemples :

- Barrage de Caderousse sur le Rhône géré par la CNR: BFUP de Lafarge a été utilisé pour reprendre le radier d'une passe du barrage et certains voiles subverticaux.
- Ponts canaux sur l'Autoroute de la Maurienne: des BFUP d'Eiffage et Vicat ont été appliqués en radier fortement incliné (pente supérieure à 10 %).
- Aménagement hydroélectrique des Bois à Chamonix géré par EDF: du BFUP d'Eiffage et Lafarge a été mis en œuvre entre des rails de chemin de fer dans la prise d'eau souterraine. Les eaux du torrent sous-glaciaire de la Mer de Glace y sont particulièrement abrasives.

Le 1^{er} retour d'expérience est globalement positif et amène à chercher de nouveaux terrains d'application des BFUP pour les ouvrages hydrauliques.

1. INTRODUCTION

UHPFRC was originally designed for thin concrete structures such as footbridges or wall panels. The first large UHPFRC project (more than 1200 m³ cast with prestressed girders) involved challenging repair work on the cooling towers of the Cattenom nuclear power plant in France. Weight and durability of the new structure were critical design factors.

As Thierry Thibaux explained at the 2009 UHPFRC Symposium [1], UHPFRC has found a place in the strengthening of rehabilitation projects. The following examples explain how UHPFRC's durability can be utilized for the construction or repair of hydraulic structures and in particular; those requiring high resistance to abrasion and impact.

2. UHPFRC IMPACT AND ABRASIVE STRENGTHS

Since water flows constantly through dams or water intakes (with debris often containing wood and stones), hydraulic structures are exposed to extremely abrasive conditions, especially during floods.

UHPFRC performs better than other traditional materials which are typically used in hydraulic projects due to the fibres – and their ability to withstand impact – as well as its matrix, which contributes to superior strength against abrasion. “ALAG” products (calcium aluminate cement with calcium aluminate synthetic aggregates) have been used for several decades in dams for their resistance to hydraulic abrasion and cavitation [2]. But these types of products lack impact resistance.

2.1 Abrasive Tests

To measure the abrasive strength, a reference test was established by CNR. The sample was placed under water and exposed to a sand jet at an angle of 45 degrees with a 3 bar pressure for 75 minutes. According to [2], those test conditions are said to be equivalent to 110,000 m³/year with 5000 tons of sand load/meter.

Glass is taken as a reference with an index value of 1; the lower the index, the better the abrasive strength.



Figure 1: UHPFRC samples after a CNR abrasive test.

Table 1: Abrasive strength of various materials

Material	Abrasive Strength (CNR test)
Granite	0.35 to 0.85
ALAG	0.4
UHPFRC	0.8
Glass	1
Ordinary concrete	3 to 4 (C60 to C30)

2.2 Impact Tests

The CNR laboratory has developed equipment to monitor impact resistance (figure 2). The ball falls 2700 times in 3 hours on the concrete specimen. This basic test simulates impact and measures the volume loss, as indicated below for various materials.

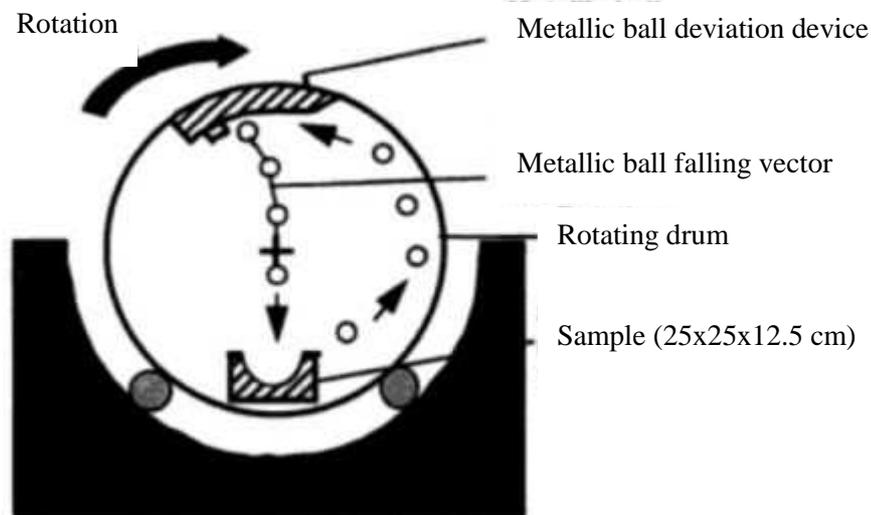


Figure 2: CNR apparatus for impact test.

Table 2: Impact resistance for various materials

Material	Impact Resistance (CNR test)
UHPFRC	23 – 70 cm ³
Granite	< 100 cm ³
ALAG	< 120 cm ³
Conventional concrete	200 cm ³ to destruction

3. RETROFIT OF CADEROUSSE AND BEAUCAIRE DAMS

In the past few years, CNR has used UHPFRC to repair dams on the Rhône River [3]. CNR operates all dams on the Rhône and has more than 3000 MW installed.

3.1 Repair of Caderousse Dam's slab

The Caderousse Dam, located near Avignon on the Rhone river. is operated by CNR. It is 176 m wide and divided into 8 gate bays, each 22 m wide. It can evacuate a maximum of

12 500 m³/s during a flood. The structure at each gate bay can be damaged by the impact of rocks during floods. The slab of gate bay number 4 was repaired in 1997 with an Abraroc product. In 2008, a study revealed that holes had appeared, between 4 and 30 cm deep over a few square meters.



Figure 3: Caderousse Dam and Gate Bay n°4.



Figure 4: UHPFRC casted with the pump on the Caderousse Dam.

In 2010, based on the performance of other UHPFRC projects, CNR decided to use UHPFRC from Lafarge with steel fibres to repair 80 m² of the slab. The contractor (Mérillon) completed the work in the following order:

- Concrete removal was required (up to a depth of 5 cm),
- Sealing of shear connectors (6/m²).
- 11 m³ of UHPFRC, mixed in a local batching plant, was transported by ready-mix trucks and pumped more than 140 m, all the way to the centre of the dam, in order to reach gate number 4.
- Cured with a special agent and covered

The gate bay opened 20 days after casting. The mechanical performance was recorded as follows:

- $R_c > 120$ MPa at 7 days, > 165 MPa at 28 days
- Abrasive test : 1.05 at 28 days
- Impact test : 23 cm^3 at 28 days

In 2012, divers were sent to survey the slab and noticed no major damage and a new gate bay was subsequently repaired.

3.2 Repair of Caderousse and Beaucaire Dams' Hydraulic Vertical Screen

On a dam, screen rakes are used to remove wood debris from the water intake bars. The Caderousse and Beaucaire Dams have been in service for almost 40 years and the top portion of their concrete walls were deteriorating, mainly due to the corrosion of steel rebars (only 2 cm cover) and carbonation of the concrete.

CNR requested a material with very low porosity in order to protect the existing rebars, with a high abrasive strength (due to the screen rake truck) and with a high early compressive strength (to restart the production rapidly). For all these reasons, a UHPFRC was chosen with 4 to 6 % porosity, abrasive strength of 0.8, and 100 MPa at 3 days.



Figure 5: Caderousse Dam's screen rakes after completion of UHPFRC repairs (light grey portion).

The contractor used UHPFRC from Lafarge on both projects; Caderousse in August, 2011 and; Beaucaire in September 2012. Two scaffolds on rails were used to work above the Rhône River. Each phase of the operation was completed during a very limited time in order to minimize the interruption of electricity production. The following steps were performed:

- Concrete removal, required up to a depth of 4 cm and sealing of shear connectors ($8/\text{m}^2$). On the Beaucaire Dam, concrete sawing was also required on the top 50 cm (**Figure 6: In-situ UHPFRC casting (Beaucaire Dam).**),
- Casting, with the use of lightweight form panels,
- In-situ batching with a small mixer (400 liters) and piston-pumping of the UHPFRC,
- Stripping after 24 hours.

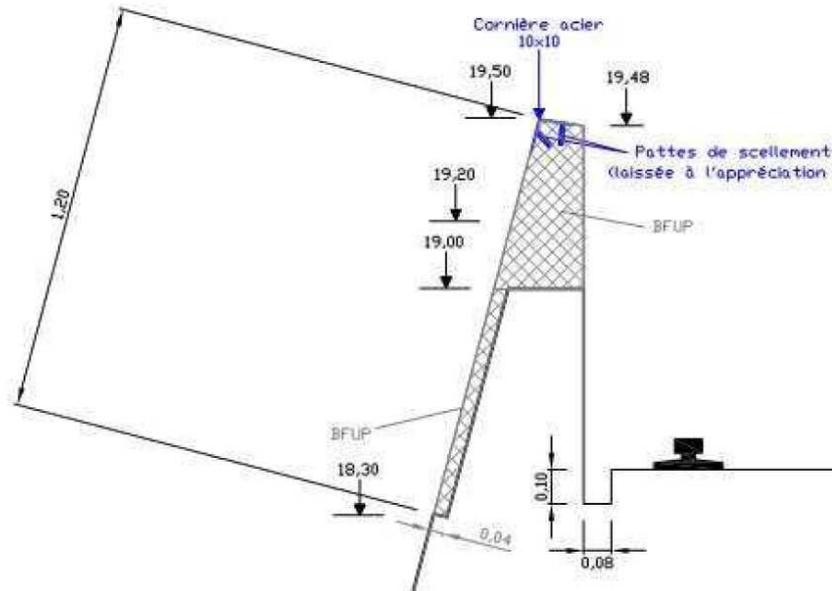


Figure 6: In-situ UHPFRC casting (Beaucaire Dam).



Figure 7: UHPFRC casting (with injection hole) and 2 scaffolds on Beaucaire Dam.

The owner was pleased with the retrofit because the construction period was short and the repairs performed as expected – when a flood occurred for the first time in November 2011 and a when a severe, cold weather period occurred in February 2012.

The biggest challenge was to ensure the important slope of one of the channel-bridge (> 10 %). Therefore, UHPC was cast with a mold covered with a polypropylene filter fabric laminated with a plastic grid. This fabric enables the air to circulate within and not the water, thereby decreasing the bug holes on the surface.

The UHPFRC from Vicat was batched in a local batching plant after its ability to produce UHPFRC was validated. The UHPFRC was delivered in ready mix trucks to the site. The mechanical characteristics of this UHPFRC (with required values by CERA in brackets) were as follows:

- $R_c > 145$ MPa at 28 days (requirement: > 130 MPa)
- Abrasive test : 1.0 at 28 days (requirement: < 1,3)
- Impact test : 28 cm^3 at 28 days (requirement: < 80 cm^3)

5. USE OF UHPFRC WITH ABRASIVE WATER OF THE ‘MER DE GLACE’

Since 1973, Electricité de France (EDF) has operated a unique hydroelectric power plant under the largest French glacier, the ‘Mer de Glace’ (‘Sea of Ice’). The plant takes up to 15 m³/s of water, has a power of 42 MW and produces enough electricity for about 50,000 people.

In the past few years, the water intake has been moved up by 1 km as the glacier is dramatically retreating due to climate change. The works were designed and followed by the Hydro Engineering Center of EDF - which gathers EDF expertise in the field of hydropower engineering. Its goals are divided in terms of both project management and contractor/ owner engineering support. The Hydro Engineering Center leads design studies on new projects, rehabilitation, reconstruction and modernization of existing works. These studies concern mainly EDF’s own hydropower installations, but their skills are also applied to projects for external customers, in France and abroad.

Under the ‘Mer de Glace’, the water is directly taken under the glacier, approximately 1560 m in elevation, and taken down to the valley of Chamonix, at an elevation of about 1100 m. The water is so full of silica flower from the moraine (glacier’s rocks) that the turbine wheel is changed twice a year, a unique case in France. The civil works are therefore under constant and severe damage.

So far, reinforced steel panels (made of Dursteel® by Produr [4]) 2 to 3 cm thick or down-graded railways filled with ALAG® concrete (in between) were used to protect the most sensitive parts.

In 2012 and 2013, UHPFRC was used along with ALAG® to compare the behavior of the two products. UHPFRC from Eiffage and Lafarge were used between horizontal railways to fill in the voids between them. The railways are 12 to 15 cm high and placed next to each other; the UHPFRC fills in the void (roughly 10 cm x 10 cm x a few meters). The main challenge was to produce the UHPFRC concrete on site, with a low temperature of 5°C and the water taken directly from the glacier, at 1°C. The structures are very deep within the galleries and only reachable by cable car. Prior testing of the eflow and compressive strength glacial water was completed prior to construction. Finally, almost 1 m³ was cast in-situ in the winter of 2012 and the same amount in the winter of 2013.

After one year of full power and a major flood (50 m³/s) due to a glacier-dammed lake breakdown (beneath the glacier), no major damage has been noticed.

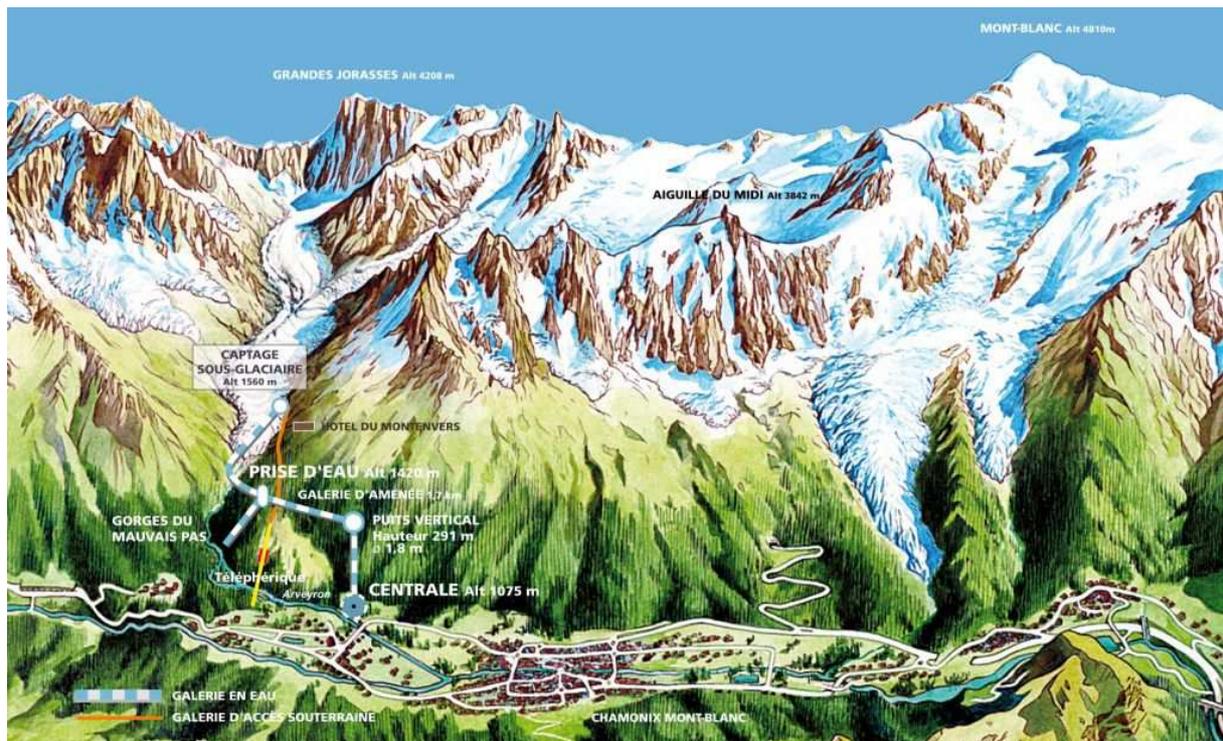


Figure 10: EDF hydroelectric power plant under the 'Mer de Glace' glacier.



Figure 11: Casting of UHPFRC between railways during the winter of 2012.

6. CONCLUSION

UHPFRC, with its high abrasion and impact resistance, is gradually gaining acceptance in hydraulic projects to replace metal reinforcement or ALAG® cementitious products. The projects presented, along with the various configurations, confirm the material's versatility.

Due to the positive results achieved, engineers and dam operators will continue to use UHPC in the future - to find new solutions for old problems.

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