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Ductal® Pont du Diable footbridge, France

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ABSTRACT: Ductal®, is a new material technology developed over the last decade that offers a combination of superior technical characteristics including strength, ductility and durability, while providing highly moldable products with a quality surface. Compressive strengths reach up to 200 MPa and flexural strengths reach up to 40 MPa.

Ductal® covers a range of formulations that can be adapted to meet specific demands of different customer segments, enhancing the usage value and contributing to the overall construction performance. By utilizing the material's unique combination of superior properties, designs can eliminate passive reinforcing steel and experience reduced global construction costs, formworks, labour and maintenance; relating to benefits such as improved site construction safety, speed of construction, extended usage life and others. A number of references on Ductal® already exist in different countries, both in structural and architectural segments. In this paper, the first use of Ductal® for footbridges in France is presented.

In Gorges de l'Herault, next to Montpellier, the 'Pont du Diable' Ductal® footbridge, designed by the architect Rudy Ricciotti was constructed. This footbridge with a span of 68 m was constructed by Freyssinet and Bonna Sabla. The transversal section is composed by two bone-shaped webs, with a height of 1,8 m, connected by a light ribbed deck. Fifteen 4,6 m length segments were prefabricated in a factory are delivered to jobsite. These elements were assembled by prestressing using 8 cables and then erected in one day.

1 INTRODUCTION

Ductal®, the outcome of the research over the last 10 years in the area of concrete, is a new construction material technology belonging to UHPFRC family, with very high durability, compressive strength, flexural resistance with ductility and aesthetics (Orange, 1999).

Through the development period, several prototypes have been produced, prior to make an extensive use in civil works, structural and architectural various applications (Behloul et al, 2004).

A material with such high mechanical and durability properties offers interesting opportunities in the field of bridges and footbridges and prestressed applications. As might be expected, the high flexural tension capacity also gives rise to extremely high shear capacity. This allows Ductal® to carry the shear load in the structure, without providing auxiliary shear reinforcement. The elimination of passive reinforcement makes it possible to use thinner sections and a wider variety of innovative and acceptable cross-sectional shapes.

Several short span bridges were constructed: 'Bridge of the Future', Washington, US – Wappello, Iowa, US- East Kyushu Expressway in Japan-Shepherd in Australia (Cavill et al, 2003) and Saint Pierre La Cour in France (Behloul et al, 2006).

Also several Ductal® footbridges were constructed round the world: Sherbrooke in Canada – Seonyu in Korea (Behloul et al, 2003)– Sermaises in France-Sakata Mirai and Akakura in Japan and Papatoetoe in New Zealand and Pont du Diable footbridge in France which will be presented in details in this paper.

2 DUCTAL® TECHNOLOGY

Ductal® is based on the principle that a material with a minimum of defects such as micro-cracks and pore spaces will achieve a greater percentage of the potential ultimate load carrying capacity defined by its component materials, and it will also have greater durability. By applying this principle as a guideline, a concrete has been proportioned to provide a very dense mixture that will minimize voids and a very high compressive strength, but with not enough ductility compared to a conventional mortar. The inclusion of adequate fibres improves drastically tensile strength and provides a substantial level of ductility.

The various Ductal® formulations are all based on an optimized composition combining homogeneity and adequate granular compactness.

To enhance and to stabilize the performances, especially mechanical ones (Table 1), the option of heat treatment can be chosen. For each application according to technical and economical challenges, adequate adjustments are made within Ductal® technology in order to achieve the most adapted product to the customer requirements.

As described above, Ductal® is an Ultra-High Performance Concrete reinforced with fibres. These fibres can be made of steel (Ductal®-FM), made of organic material (Ductal®-FO) or combination of both steel and organic material (Ductal® AF).

The fresh mixes of all these ranges of material have very useful properties in term of fluidity and self placing. Most of the standard industrial batching facilities are able to mix Ductal® requiring only minor adjustments.

Ductal®-FM, used for structural applications, includes small steel fibres at a dosage of 2% per volume, and of 0.20 mm in diameter and 12 mm in length. In a typical load deflection graph of a sample under three-point loading, the material exhibits linear behaviour up to its first crack stress, a post-first-crack strain hardening phase up to its ultimate flexural load, and a post-ultimate-load strain softening phase. It has an ultimate bending stress that is over twice its first crack stress and more than ten times the ultimate stress of conventional concrete (Fig. 1).

The Ductal® microstructure is completely closed, making it resistant to abrasion, corrosion or chemical attacks. Such superior characteristics give the material ultra-high performance durability properties (Behloul et al, 2007). The table 2 hereafter shows

Table 1. Main properties (mean values) of the material with steel or organic fibres.

	Ductal®-FM or Ductal®-AF with thermal treatment	Ductal®-FO without thermal treatment
Density	2500 kg/m^3	2350 kg/m^3
Compressive strength	180–200 MPa	130–160 MPa
Flexural strength (4*4*16 cm)	40–45 MPa	18–25 MPa
Tensile strength	11 MPa	8 MPa
Residual tensile strength (0.3 mm)	10 MPa	4 MPa
Young Modulus (E)	50 GPa	45 GPa
Poisson Ratio	0.2	0.2
Shrinkage	<10 μm/m	550 μm/m
Creep factor	0.3	0.8
Thermal expansion coefficient	11.8 μm/m/°C	11.8 μm/m/°C

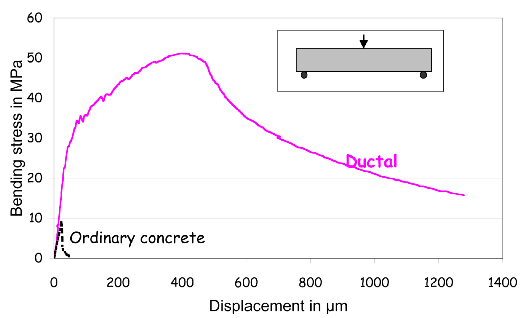

Figure 1. Ductal®-FM behaviour in bending.

Table 2. Ductal® main durability properties.

Durability indicator	Ordinary concrete	HPC	Ductal®-FM
Water porosity (%)	12–16	9–12	2–6
Oxygen permeability(m^2)	10^{-15}–10^{-16}	10^{-17}	$<10^{-19}$
Carbonation depth (mm);one month of accelerated tests	10	2	<0.1
Abrasion test $I = V/V_{glass}$	4	2.8	1.3–1.7

some durability properties of heat treated Ductal®-FM and a comparison with ordinary concrete and high performance concrete properties.

3 DUCTAL® APPLICATIONS

The ultra high performance of Ductal® opens applications in following different domains:

- Structural applications
- Durability oriented applications
- Architectural applications

3.1 *Structural applications*

As stated in the introduction, several traffic bridges and footbridges were constructed round the world. For these applications, the combination with prestressing allowed to design thin and slender structures. The material allows the reduction of the dead load by a factor three.

Ductal® can also be used in structural applications without any passive reinforcement, or prestressing, like the case of stairs. The material was used in several projects: stairs at Roissy airport in Paris, stairs at new Lafarge office in Birmingham, and a new helicoidal stair solution developed by an industrial partner, Escaliers Decors (Fig. 2).

Figure 2. Stairs made of Ductal.

3.2 *Durability oriented applications*

The durability of Ductal® is as important as the mechanical strength. Combining strength and durability, Ductal® can be an ideal solution for structures in severe environment. Also the durability of the material lowers the maintenance costs and makes the solution very competitive.

Ductal® was used in several durability/fire resistance oriented applications like the beams and girders (more than 2000) used for the Cattenom power plant cooling tower-France, the retained earth anchorages (more than 6000) used in Reunion Island – France- and the Ductal®-AF used for the construction of composite columns in the Reina Sofia Museum in Madrid (Spain). Recently Ductal® was used for the fabrication of the troughs of Gold Bar waste water treatment.

The Gold Bar wastewater treatment plant in Edmonton, AB, Canada, is the sole facility serving the city of Edmonton and its surrounding suburbs. The plant's collection tanks are located directly over the sheet-steel plate-settlers; structural strength, durability and lightness were there-fore key requirements. Traditional cement would have called for extra support and stainless steel might have seemed the logical choice for this project, but the cost was prohibitive. The Stantec design consultants were familiar with Ductal's unique properties and decided that Ductal® troughs offered a viable, new solution. 200 pieces of Ductal®-FM U-shaped forms, 5 m long, 800 mm high, 600 mm wide, 17 mm thick were made and installed (Fig. 3).

3.3 *Architectural applications*

The use of a concrete-like material but with almost unlimited possibilities of appearance, texture and colour has excited the architects by giving them access to unexpected new world of shapes and volumes. Ductal® was used in several architecturally oriented applications like the bus shelters in Tucson (USA), sun shades in France, façade panels in Monaco, Kyoto clock tower in Japan and the canopies of LRT station

Figure 3. Gold Bar troughs.

Figure 4. Sun shades for Clichy swimming pool.

Figure 5. Ductal® roof of Navarra house.

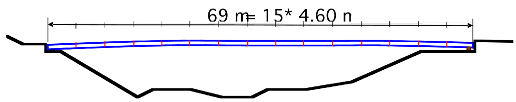

Figure 6. Longitudinal view of the footbridge.

of Shawnessy in Canada. Recently, Ductal® was used for the construction of several projects: cladding at Thiais, sunshades at Clichy, Badia Berger mantialla at Paris and Navarra roof house at Muy.

– Sunscreens at Clichy
  The Clichy municipal swimming pool was built in 1968 and required extensive work. The Town Hall opted for refurbishing including reconstruction of the south-facing, fully glazed main facade.
  ENIA Architects suggested the installation of outside sunscreens to control the solar impact and, accordingly, the thermal ambiance in the pool. This new double skin is made up of a grid of horizontal and vertical slats of Ductal®, of 4 cm in thickness, forming rectangular modules (L. 2.50 × H. 1 m) mounted to the existing metal structure (Fig. 4).
– Navarra roof house
  Dreamt up by Rudy Ricciotti for art dealer Enrico Navarra, the roof over the art gallery in Muy en Provence represents a new technological achievement for Ductal®. Large dark panels with a "stealth" look will soon cover the entire gallery with a 7.7 m overhang. Each segment of Ductal® weighs in at 3 tons and has been given heat treatment at 90°. The roof is a world-first, only 3 cm thick at the edge of the overhang and 40 m wide, providing an extreme visual contribution to the landscape (Fig. 5).

4 DESCRIPTION OF THE PONT DU DIABLE FOOTBRIDGE

The Gorge de l'Hérault is a highly cultural region, with various important features. First of all, the river Hérault with its meanders has drawn an irregular gap between the two shores. A rich and miscellaneous flora and fauna are still present and had to be protected through out this project.

Second, the Gorge de l'Hérault is a popular tourist area with the oldest stone bridge in roman style (around 1036). According to the legend, the devil didn't manage to destroy it. It left the name to the whole site – the devil's bridge. Recently in the late decades, a prestressed concrete bridge was erected in order to carry traffic loads.

The Pont du Diable footbridge is designed for pedestrians and cyclists. The breach to overcome is about 68 m long and 10 m high (Fig. 6). The consideration of site features brought the idea of a single span bridge with no intermediary support, thus minimizing the impact on natural surrounding. No dilatation joint and limited effort through ground foundation led the project to a simple and articulated beam with free displacement at one shore.

Moreover, the use of a high performing concrete with post-tensioned process along two beams that form handrail, allows a minimum visual impact through very small static height.

Together with the two other bridges, the use of UHPFRC concrete with new construction methods could retrace the different evolution in construction process over a unique site.

The cross section is composed by two bone-shaped webs, with a height of 1,8 m (Fig. 7) and a web thickness of 12 cm. These two beams are used as a parapet and include random openings. The footbridge is entirely made of Ductal®. The total length of 69 m is composed by fifteen 4,6 m length identical segments prefabricated in a factory. Each segment is a monolithical component including the 2 vertical beams, three

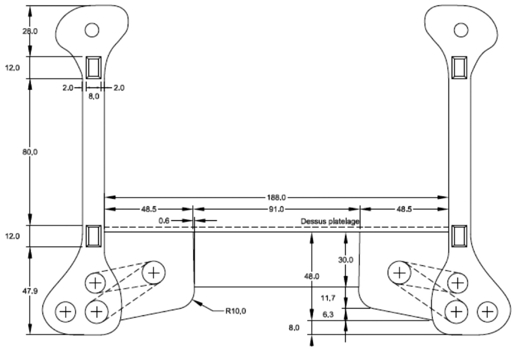

Figure 7. Transversal section.

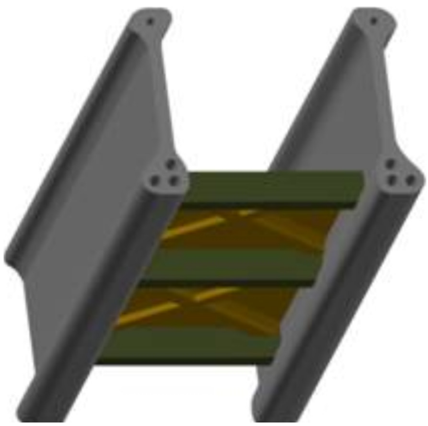

Figure 8. 3D view of a segment.

transversal ribs (Fig. 8). A Ductal deck of 3 cm in thickness with cross transversal ribs is fixed to the segment. The transversal ribs allow the horizontal wind bracing of the structure.

The structure is prestressed using 8 Freyssinet Gamme C cables. 13C15 and 19C15 units are used in the lower part and a 4C15 unit is used in the upper part.

BFUP design rules (BFUP, 2002) are used for the calculation of the footbridge. The simple single span structure design allows the use of accurate analytic and mathematical resolution model. Thus, dynamics response of the footbridge is perfectly known and the impact of the various parameters can be easily quantified through a simple mass spring system. The natural frequencies can be numerically fixed outside the critical field for pedestrians. Acceleration feeling remains theoretically weak. Though, the thickness and flexibility of the footbridge shows a critical behaviour towards wind loading with turbulent flows. The vibrations under lateral vortex are all the more sensible that the structure remains always compressed and no energy is dissipated. Since the damping ratio of Ductal® is very small, the most efficient way to solve this issue is to mount tuned mass dampers at the midpoint of the structure. Dynamic responses were studied both theoretically and through wind tunnel experiments showing convergent results.

Figure 9. Prototype segment.

5 PREFABRICATION AND ERECTION

The footbridge is composed by 15 segments of 4.60 m in length for each. These segments are prefabricated at Bonna Sabla facilities next to Vendargues. Steel mould with accurate precision ±0.5 mm is used.

The Ductal material is mixed in a traditional mixer in batches of 0.8 m3. In total 4 batchs are needed for one segment. A plunging tube is used to fill the mould. After fabrication, the segment is kept in the mould during 24 hours for curing. After demoulding, the segment is heat treated in steam at 90°C during 48 hours. Two segments are fabricated a week.

As recommended by the BFUP design rules, suitability tests are performed prior to the launching of the fabrication. A prototype segment of 1 m in length is fabricated by Bonna Sabla (Fig. 9). Samples are first cored in the segment and then tested at Lafarge Laboratory to check the properties of the material. These tests allow to determine the fibre distribution effect on the properties (K-factor) and to validate the calculation hypothesis. This procedure is similar to that one used for the Saint Pierre La Cour Ductal traffic bridge (Behloul et al, 2006).

After fabrication, two pieces of the Ductal precast slab are fixed to the segments. This solution allows the stiffening of the segments which makes easy their handling and transportation. To complete the stiffening of the segment, temporary steel transverse beams are fixed at the top of the webs to prevent buckling and transversal deformation (Fig. 10).

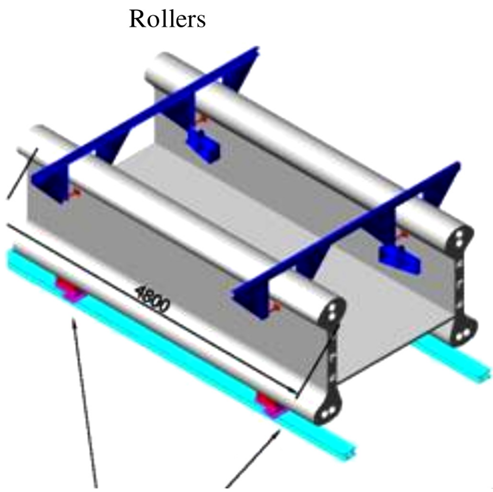

Figure 10. 3D view of a segment.

After these operations, the segments are transported to jobsite two by two on a truck. A Layer-type scaffolding along the footbridge is installed. This scaffolding is composed by 2 HEB steel girders supporting transverse concrete beams.

The Ductal segments, of 9 tons each, are positioned on the scaffolding using a small crane. Each segment is positioned using 3 rollers for which the position can be adjusted using screws.

The cables are installed. The strands are prestressed one by one using a small jack because of the lack of space. The complementary Ductal precast slabs are then installed and fixed. Finally, the tuned mass dampers are installed.

6 CONCLUSION

Ductal® is a new technology of ultra high strength concretes that constitutes a breakthrough in concrete mix design. This family of products is characterised by a very dense microstructure and very high compressive strength achieving and possibly exceeding 200 MPa. Steel and organic fibres or combination of both are one of the major components of the material enhancing the bending strength, the ductility and fire resistance.

The three main categories of applications are:

- Structural applications: The very high mechanical properties combined with prestressing technology offer to engineers and architects lot of opportunities to design elegant structures by avoiding heavy steel reinforcement.
- Durability oriented applications: the very dense microstructure of the Ductal® matrix offers a material which resists to very aggressive media and opens therefore a very wide range of applications.
- Architectural applications: a very wide range of textures and colours effects are accessible to Ductal®. Such properties provide architects with very high potential of innovative design in all elements that build up new architecture.

A number of references on Ductal® already exist in different countries (Behloul, 2008), both in structural and architectural segments.

The 'Pont du Diable' Ductal® footbridge, designed by the architect Rudy Ricciotti, is the first UHPFRC footbridge in France. The aspect ratio span/height equals 38. Such high ratio is very difficult to obtain with concrete-like structure or steel structure. This project demonstrates that Ductal pushes the limits of structure design and makes possible the dreams of the architects.

This footbridge will be inaugurated during spring 2008.

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