New UHPC for the realization of complex elements

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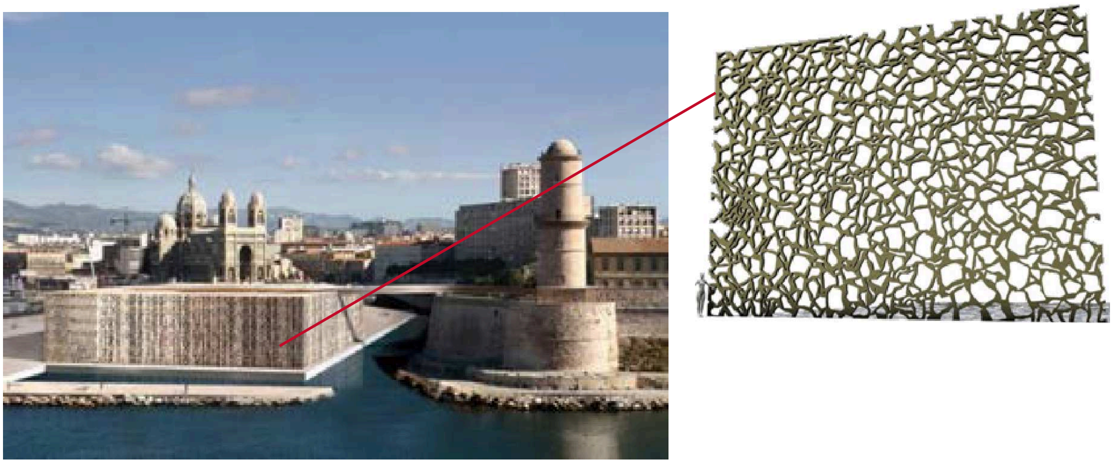
Abstract

UHPC, or Ultra High Performance Concrete, is a class of concrete defined by its exceptionally high mechanical performances, durability and refined aesthetics. Thanks to these characteristics and many project references, the worldwide development of UHPC, such as Ductal®, is increasing since few years. Ductal® can be used either as a precast material or cast in-situ, for new constructions or renovations. The range of applications is very large, from structural components to architectural façade, through the urban furniture, sunshades, etc. A significant R&D program led to the development of customized formulations that meet the constraints of the projects and customers' expectations. Various type of fibers can be used (metallic, organic, glass), for the formulations which can be either self-compacting or sprayable or even take a slope. Sprayed Ductal® offer news possibilities for the realization of 3D complex elements, for which the mold represents an important cost. The mechanical and durability performances allow an optimization of the dimensions (reduction of the thickness or increasing of the length and width). The watertightness for a façade for example could also be appreciated.

INTRODUCTION

The unique combination of high compressive strength, self-placing properties, extreme durability, ductility, and aesthetics make Ductal® a truly revolutionary construction material. In the past 10 years, it has been shown that these properties have allowed designers to exploit elegant architectural designs that would otherwise have been only accessible to high-strength steel or to complex materials systems. Figure 1 shows several architectural projects in Ductal®, highlighting applications in thin shells and perforated panels; others examples can be found in Ref. [1].

(a) (b) (c)



(c) (d)

***Figure 1:** Examples of architectural applications in Ductal®: a) thin-shelled canopies at Shawnessy LRT station in Calgary (2004); b) perforated façade panels in the ZAC apartment building in Paris; c) perforated roof and envelope of the future Jean Bouin Stadium near Paris (model, Ref. [2]); d) perforated façade panels and footbridge at the MuCEM in Marseille.*

We have recently developed a self-placing Ductal® for architectural application based on glass fibers. The interest of using glass fibers is its higher tensile strength (approximately 1700 MPa) compared to organic fibers, lower cost compared to steel fibers, and that it does not rust in surface a major aesthetic impediment to using steel fibers in white Ductal® in Ref. [2]. It was furthermore shown that the composite maintained its ductile performance in wet conditions (submerged in 50 °C water for 3 months). This property is not generally associated with normal glass-reinforced composites (GRC), which have some trouble from embrittlement with wet aging [4]. Collectively, these mechanical properties for our glass fiber-reinforced Ductal® (GF- Ductal®) should allow for greater freedom in structural design of architectural applications.

As part of constantly developing the options for fabricating elements in Ductal®, Lafarge has perfected a new formulation with flow characteristics that allow it to be applied as a spray without compromising any of the technical performances or aesthetic qualities of the cast solutions. An ultra-high performance concrete from Ductal® range suitable for sprayed GRC devices (sprayed Ductal®) has been developed by managing optimization of the skeleton to reach mechanical and rheological performance. It is the story of a long-awaited innovation.

RESEARCH SIGNIFICANCE

Ductal® is a family of self-leveling ultra-high performance concretes that provide a unique combination of superior properties including strength, ductility, durability and aesthetics. By utilizing its unique combination of properties, designers can create thinner sections and longer spans that are lighter, more graceful and innovative in geometry and form, while providing improved durability and impermeability against corrosion, abrasion and impact. Many economies gained are a result of engineering new solutions for old problems. Advantages may include: reduced global construction costs, formworks, labor and maintenance; relating to improved site construction safety, speed of construction and extended usage life.

The new thermal regulation and new architectural concepts promote an increase of need in the façade market with its impact under panel market. As well known, there are two processes to obtain cement based panels. Panel can be produce over a pouring method or by using specific sprayed device. The pouring solution has been already treated in 2012 at the Lafarge Research Center (LRC). A Ductal® solution is then allowed and more details are available in the Ref [2]. This article presents major information on the development of the new sprayed Ductal® done at LRC.

The sprayed concrete technique has a long history of being used to produce complex components (special one-piece shapes). The technique is used by many precasters because it allows them to create lightweight elements without the need for heavy shuttering that can sometimes pose difficulties. The development of sprayed Ductal® targeted this requirement by focusing particularly on applications that would enable the design of lightweight facades in an enormous range of forms and colors to create architecture consistent with the existing urban fabric. Sprayed Ductal® offer news possibilities for the realization of 3D complex elements, for which the mold represents an important cost. The durability performances allow an optimization of the dimensions (reduction of the thickness or increasing of the length and width). The watertightness for a façade for example could also be appreciated.

The central challenge was to achieve the practical implementation flexibility offered by the spraying technique by designing a sprayable Ductal® solution whose finish, durability and strength go way beyond those of the kind of concretes traditionally sprayed. By its very nature, Ductal® is a self-placing concrete that flows very easily into shuttering and molds for optimum filling and high-quality finish and texture. The R&D team therefore got to work on designing a new range of Ductal® products with flow characteristics suitable for the fabrication processes used by our partners. A Ductal® formulation that is fluid enough to be sprayed, but stays in position on a vertical wall, makes it possible to have the best of both worlds. The real innovation here is the ability to produce a concrete that performs identically to a cast Ductal® formulation, but has flow characteristics that are fully adjustable to fabrication processes.

DESIGN OF THE SPRAYABLE DUCTAL

General conditions of the GRC sprayed process

Glass fiber reinforced concrete consists of high strength glass fiber embedded in a cementitious matrix. In this form, both fibers and matrix retain their physical and chemical identities, while offering a synergism. Fibers are the principal load-carrying member post-crack, while the surrounding matrix promotes the elastic behavior and keeps them in the desired locations and orientation, acting as a load transfer medium between the fibers and protecting them from environmental. Glass fibers can be incorporated into a matrix either in continuous or discontinuous (chopped) lengths.

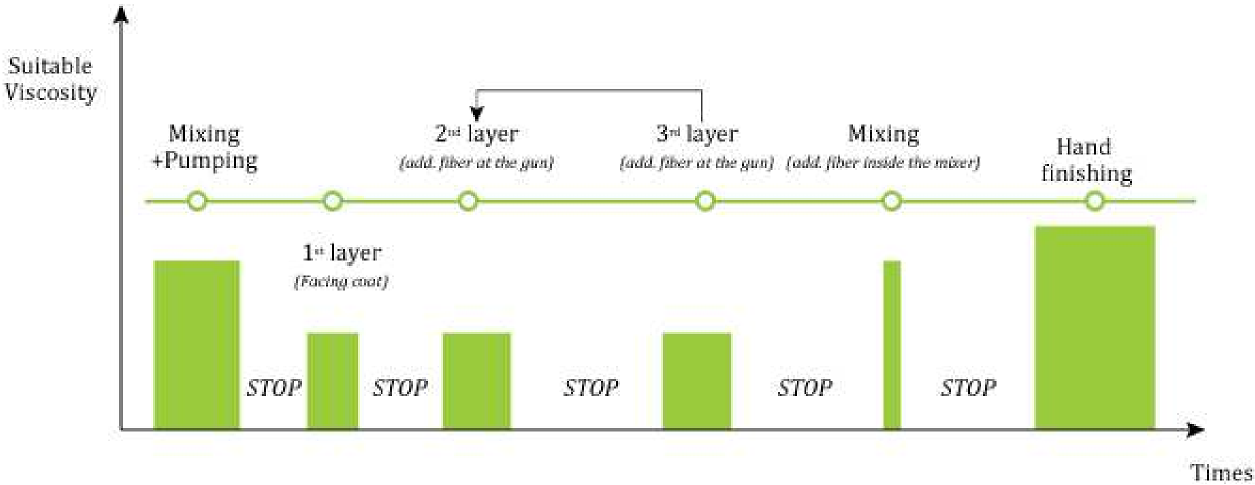


Figure 2: *Schematic representaion of the shotcreting process expectation in term of suitable mortar viscosity over the times.*

The specification of sprayed production is due to its multilayers composition as schematically proposed at the Figure 2. The final thickness is obtained by a series of sprayed layers compacted by roller:

1. In the process of sprayed GRC, the mortar is produced separately from the fibers.
2. The first layer named gel or facing coat is made by using spray gun which sprays mortar fed from a "mortar" pump without any fibers and its thickness is less than 3 mm. In some case, specific gun are used.
3. The second layers is made by using spray gun which sprays mortar fed from a "mortar" pump and "glass fibers" cut in the spray gun from Roving. The gun is a concentric spray gun.
4. The GRC panel is built up in thin layers by reproduce phase 3 until the required thickness is achieved - normally 10 - 15mm. Simple hand rollers are used to compact the material between layers.
5. During each step, the mortar will be stored in the tank of the pump and inside the hose which supply the sprayed gun. The cleaning of all the system is not allowed between each stop because of the time delay and the loss of material in the operation.
6. The last step consists of a reinforced mortar deposit on the surface. It permits to fix the anchors for further transportation phases and to finishing by hand the panel (angle, stiffening operations). The fibers used are different than the ones used during sprayed process. They are generally shorter and mixing with the mortar to produce a stiff mortar able to glue with exposed surface of the last sprayed layers. This operation could occur after many minutes after the last sprayed operation.
7. The time needed to produce panel is a function of the size of the panel and of the organization of the precaster.

This schematic description of the process permits to establish the first specifications of an effective solution:

- **The concrete gave to support the Stop and Go process:** Thixotropic behavior should be avoided.
- **Adhesion between layers is crucial:** Accelerator cannot be used because of multilayers application

- **Practices and control of process is a big part for the quality of the panel:** The process should remain the same (cost of pump/gun device). Replacement of GRC by Ductal should be "transparent" for the users
- In addition, because of its mechanical performance, the sprayed Ductal® should be able to be used for the production of large panel: rheology retention time should be at least about 2 hours.

Rheological profile requirement for sprayed application

To develop a satisfactory wet-mixture for sprayed process, the fresh properties of mortar are controlled to be suitable with the overall process. The sprayed process is a more complex than the previous description indicates. The given rheological profile of the sprayed GRC has to be identified. The first step of the research was dedicated to understand the adequate profile. Exchanges with partners were essential. The "know-how" is a secret garden develops over the years and mainly based on best practices. The translation between technical meanings and scientific objects were the main issues and it gave us lots of new idea. The question was "What really means rheological profile for users of sprayed-GRC device?"

Typical GRC mortars were sample at different steps of the production and during different periods of the production. Some of them were suitable and some others don't help us to define effective criteria. A rheological characterization was done using a rheometer made by Anton Paar. The RheolabQC is a rotational rheometer which works according to the Searle principle. It consists of a high-precision encoder and a highly dynamic EC motor, which is also used in the MCR rheometer series. You can select between controlled shear rate (CR) and controlled shear stress (CS) test settings, options which are usually only available with high-end research rheometers. The first option was used in our case.

The Figure 3 proposes an answer and help people to translate what mean "rheological profile" and needed performance at each step of the process in link with the description. Three parameters have to be considered:

1. **Yield stress above 100 Pa.** The yield stress describes the ability of the mortar to stick on the vertical surface without flowing along the surface.
2. **Rheo-thinning behavior : Reduction of viscosity with increase of shear rate.** This step is really crucial. When the fibers are projected on the surface with mortar, the lake of compaction has to be compensated by the roller. The movement of mortar around the fiber will reduce porosity and consequently increase adhesion.
3. **Viscosity lower than 23 Pa.s at 15s^{-1}**. The shear-thinning behavior is needed at many steps of the process. The problems induce by a too high viscosity will be incapacity to pump the mortar, high level of rebound of the fibers and finally lake of adhesion between each layers of mortar

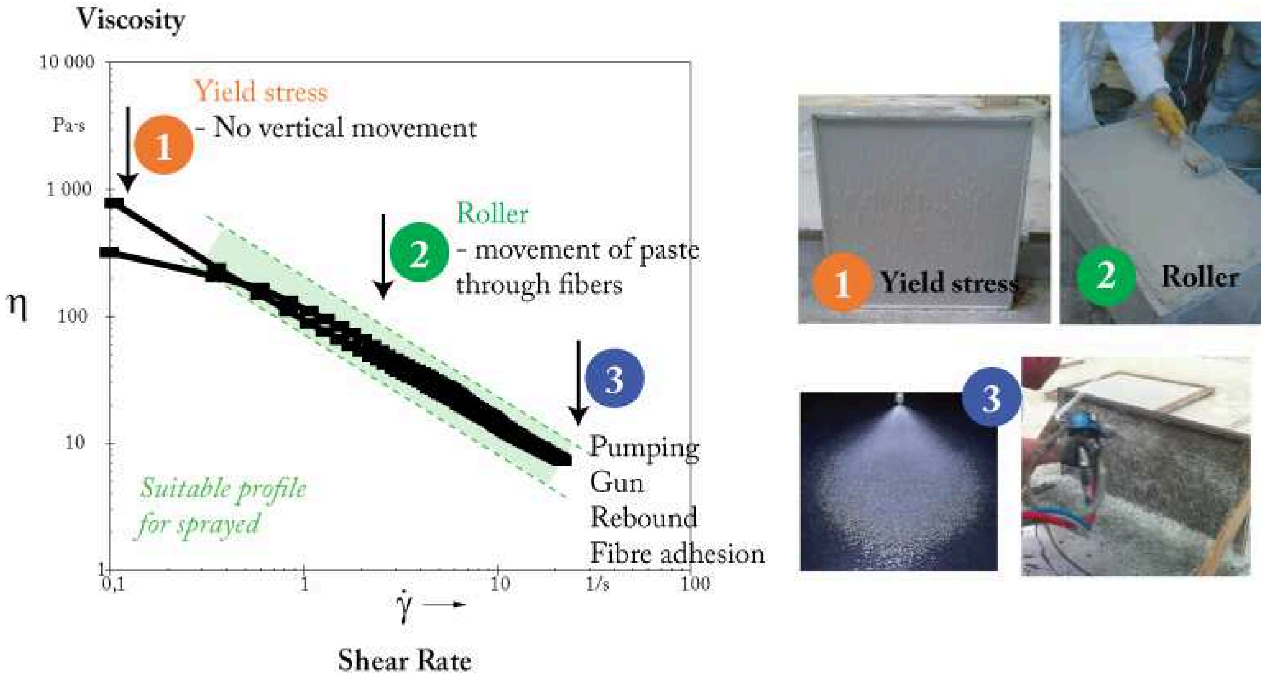


Figure 3: *Schematic description of expected rheological profile for the GRC process*

During our research, we faced those problems. Following pictures (Figure 4), four typical defects (4) were presented. In the first case, the inner dimension of mortar nozzle head (less than 1.6 mm) induces high level of shear stress on the mortar which produces blockage of pumping. Cleaning operations have to be done to restart the pump. In the second illustration, the yield stress was too low to support 2 layers of reinforced mortar. After the deposit of the second layers, a lake of cohesion occurs between the facing coat and the mold. In the third illustration, the facing coat is made with big particles. The finishing was really poor because of big pores on the surface. Consequently, as seen in the last illustration, the rebound was higher than expected with two (2) consequences: a lake of adhesion between fiber and mortar and a reduced dosage of fiber in the final panel (low ductility).

(a)

b)

(c)

(d)

Figure 4: *Examples of rheological problems to due to inadequate viscosity (too high)*
(a) Accumulation of mortar in the gun because of too high viscosity under high pressure
(b) Falling of the mortar because of too low yield stress, (c) Big spot of mortar because of lake of atomization of the mortar, (d) High rebound of fibers on the surface because of too high viscosity

Rheological profile: A gulf between GRC and self-leveling Ductal®

To understand the works done to develop sprayed Ductal®, a look on the difference of the rheological profile between the self-leveling Ductal® and the typical GRC will be useful (see at Figure 5). By definition, the main property of a self-leveling Ductal® is to have no yield stress and viscosity remains the same whatever the level of stress we apply on it. But, to reach ultra-high performance, the entire particles skeleton is optimized to reduce as much as possible the porosity in hard state. The counterbalance of this mix-design approach is known as producing materials with a rheothickening behavior (apparent high viscosity at high shear rate). The viscosity or thixotropic agents are not applicable because they increase viscosity without promote a real yield stress. Nevertheless the effort of admixtures producers, the water remains the best products to reduced viscosity. Increasing the dosage of water will produce lower viscosity. But, in the same time, it will reduce performance without promote yield stress of a self-leveling Ductal®. All those observations seem to make incompatible the used of self-leveling Ductal® of vertical sprayed process.

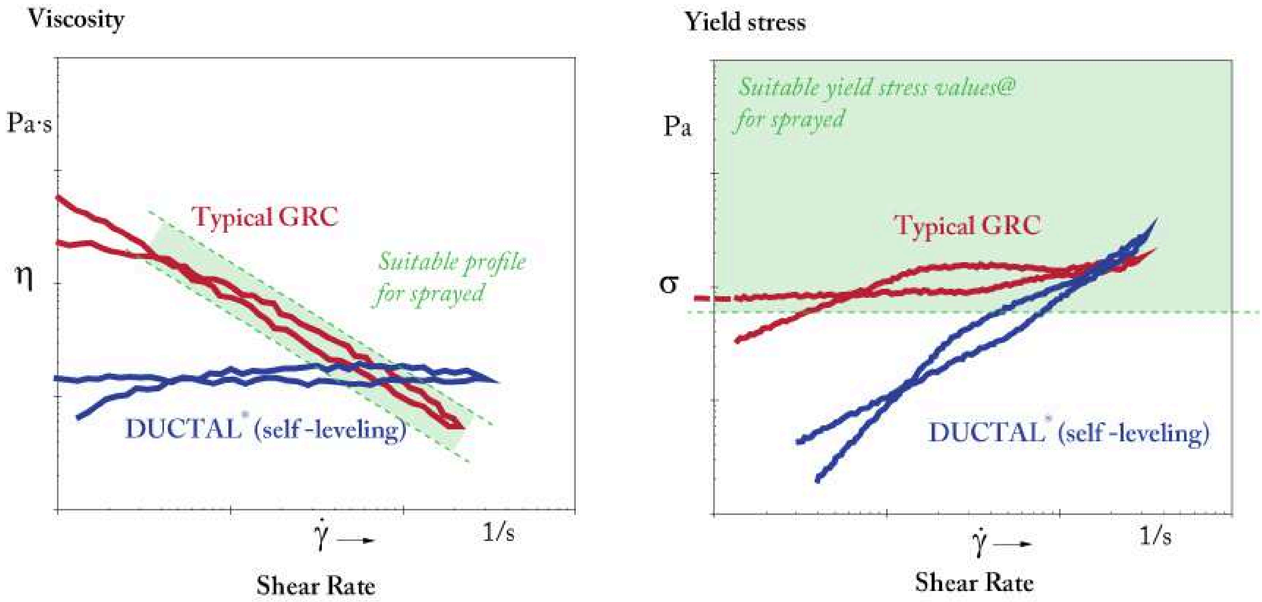


Figure 5: *Rheological profile comparison between a self-leveling Ductal® and typical GRC*

Customized formulations

Because of the need to be commercialized quickly, the sprayable- Ductal® is made with existing already available in the market. The sprayable- Ductal® matrix contained fine sand (0–1 mm), a cement, and a mix of ultrafines, which included varying amounts silica fume, metakaolin, and filler. A superplasticizer was also used. The fibers were alkali resistant (AR) glass fibers with a length of 25 mm and a dosage of 5.0 vol %. Fibers were sprayed with the UHPC mortar at the same time through the concentric gun. Because of architectural applications of such concrete, the effect of pigment additions has been study. In the range of colored proposes at the Figure 6, suitable mix design were obtained.

Figure 6: *Example of colored surfaces obtained with pigment addition*

As explained, the mixes have to be seen as a normal GRC from the process point of view which means reach the suitable rheological profile. These contrasting fluid properties need to be achieved at given concentrations of ingredients determined by skeleton optimization of all the particles. The chosen approach was based on rethinking the overall mix design formula. Without totally highlighted the methodology, the guidance of the new mix design is to control the size distribution of all the particles to have a low porosity in the hard stage and adjusts the flocculation rate of particles to create yield stress. The main issue it to enable reversible flocculation/de-flocculation phase to obtain the shear-thinning profile over each operations. To achieve an appropriate flocculation, a specific concentration of existing commercial chemical admixtures to disperse/stabilize the cement particles will be determined. Then, to induce the reverse flocculation state, particles which have specific size and shape, will also be used. Although the irregularly of the shaped particle may enhance the viscosity of mortar, the small size of particles will contribute to reduction of the viscosity by freeing the water between the cement particles.

From the lab to real life

Once we had unlocked the science, we validated the benefits of these formulations on two different scales. We began on a small scale with an industrial production site set up at the LRC with a spray chamber (see Figure 7a), pumping system and spray system identical to those used by our customers. We then worked in conjunction with an external partner to refine the requirements and arrive at a full-scale prototype (see Figure 7c,d).

(a)

(b)

(c)

(d)

Figure 7 : *(a) Sprayed setup at LRC and (b) examples of gray mix design apply in vertical application, (c) example of white3D panel produced at partner's site (Betsinor, France), (d) example of brown 3D panel produced at partner's site (Betsinor, France)*

CHARACTERISTICS

Global properties of sprayed- Ductal® mixes

In order to guarantee the properties of these new materials to our customers, we worked with the French Scientific and Technical Center for Building (CSTB) on a Preliminary Technical Evaluation of Material (ETPM). The agreement has been delivered on October 2014 by the CSTB. That will provide a complete characterization of our materials in terms of their mechanical performance and durability indicators. This characterization process was conducted using elements produced both at the LRC and by our partners, because the elements used must be representative of real-life industrial production.

The Table 1 summarize the main characteristic of the sprayed-Ductal® observed under sample produce at our partners producing site and claims inside the ETPM made with CSTB. The performance of this new Ductal® product range is above the existing solution in GRC industries. The higher rigidity permits to change the design of panel and then the maximal size of panel as it was done (see at the Figure 7 c, d).

Table 1 : Results of the characterization for the sprayed Ductal®

Reinforced matrix (5.0 % fibers)	Unit	Sprayed Ductal®
Drying shrinkage	(µm/m)	-700
Autogenious shrinkage	(µm/m)	-370
Compressive strength at 28d at 90d	(MPa)	 >100 >110
LOP Tensile strength at 24h at 28d	(MPa)	 >7.0 >12
MOR tensile strength at 24h at 28d	(MPa)	 >11 >18
Young Modulus at 28d	(GPa)	>30
Water porosity of the matrix at 28d	(%)	5 (very high durability)
Chloride diffusion at 28d	(10^{-12} .s^{-1})	0,13 (very high durability)
Permeability at 28d	(10^{-18})	0.5 (very high durability)

Tensile strength from back analysis of flexural results

The sprayable Ductal® was used to produce 700×700×20 mm plate molds. After demolding at 24 hours, 3 plate specimens measuring 450*145*20 mm were cut from each of the large plates. The resulting plates were then placed in a curing chamber at 20°C and 100% RH.

At 28 days, all 4 plates were tested in four-point bending (see Figure 8), with an inner span of 140 mm, and an outer span of 420 mm. With the use of an attached LVDT sensor, the flexural tests were deflection controlled at a constant rate of 0.1 mm/min.

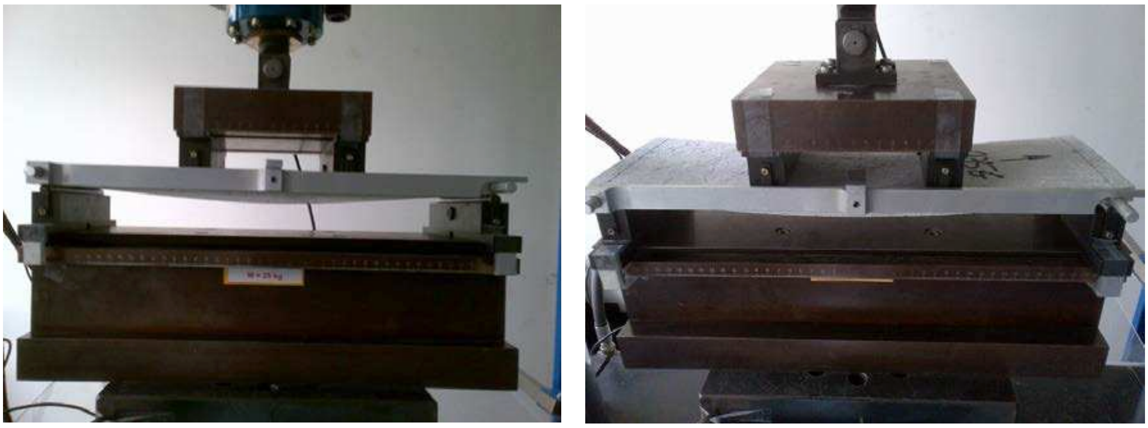
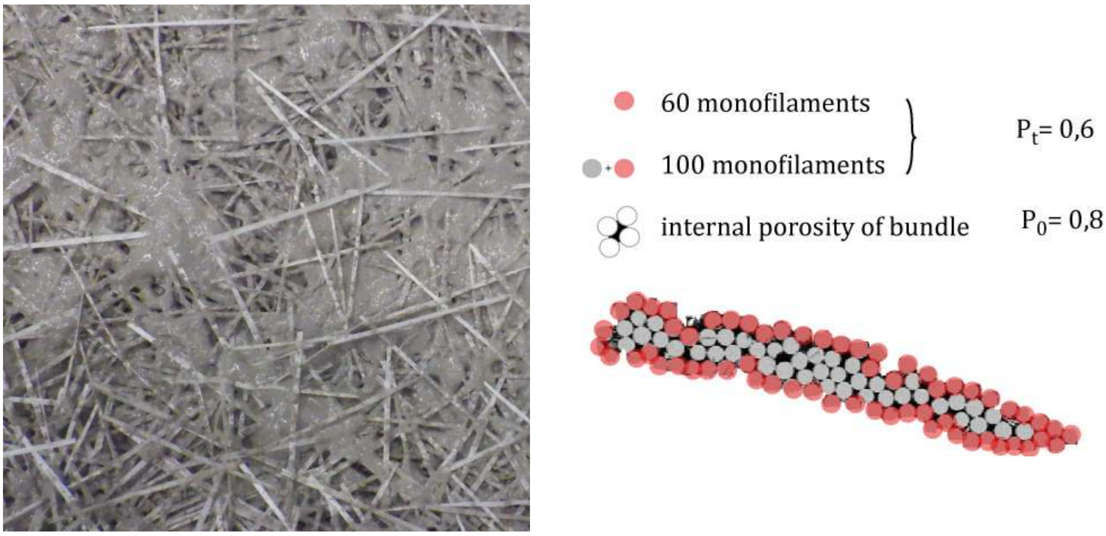


Figure 8: *Four bending test. Example of deflection observed with sprayed Ductal® mixes at 28d*

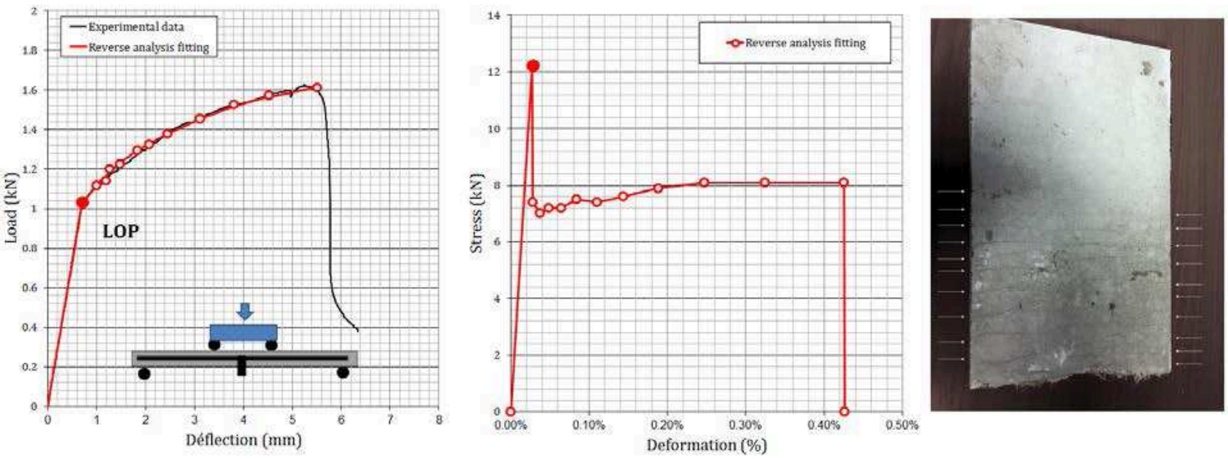
The potential contribution of the fibers to the tensile strength of the composite can be estimated by a simplified analysis, as well as by a back analysis of the flexural results.
A simplified approach to estimating the upper bound of the contribution of the fibers, σ_p, to the tensile strength of the composite is:



(a) (b)

Figure 9: *(a) Random orientation of fiber after sprayed and (b) the porosity (in black) of the bundle is closed to 20% of total volume ie =0,8*

Figure 10b shows that the reinforcement provided by glass fibers is close to a constant post-crack strength until a certain level of ultimate strain. This post-crack strength is approximately 8 MPa for the samples at 20°C. The direct tensile strength of the composite both solutions was closed to 12 MPa



(a) (b) (c)

Figure 10: *(a) Flexural loading versus deflection curves of sprayable-Ductal® mixture at 28 days (experimental vs reverse analysis fit), (b) Uniaxial tensile stress versus strain curves of sprayable Ductal® mixture at 28 days based on reverse analysis, (c) Multi-cracking pattern observed on the tensile face of plate after a flexural test*

Materials design criteria for deflection-hardening fiber-reinforced plates.

The ultimate objective in designing a thin plate element subject to bending is to ensure a 'structural ductility' of the element that is, the ability of an element to safely deflect under loads without failing in a brittle manner. The ideal load-deflection behaviour of a material is thus a deflection-hardening response with sufficient ultimate deflection. An analysis presented below outlines a simple criterion based on the materials properties of the composite to ensure a deflection-hardening response in bending.

It should be noted that, in addition to materials properties, the size of the specimen is also important in determining the ductility of a structural element. For example, increasing the length of a plate element increases the zone where multicracking can occur, thereby increasing the opportunity for a deflection hardening response. Roughly, under the same loading conditions, and for a given plate thickness, the ultimate deflection scales with the square of the span.

To derive criteria for deflection hardening, consider a rectangular section of height, h, subject to bending. Figure 11 shows the stress distribution of the section at the moment a crack has formed and propagated to a height, αh. Three zones are created in the plate: i) an elastic, compressive zone above the neutral axis at α; ii) an elastic tensile zone, below the neutral axis and above the crack, with a maximum tensile stress, σ_t ; and iii) a damaged zone with a uniform tensile stress of σ_f distributed along the face of the crack.

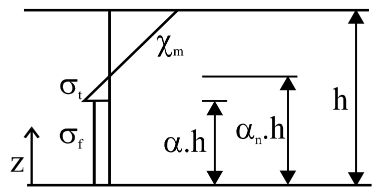


Figure 11: *Stress distribution in a cracked section subject to bending*

Considering mechanical equilibrium, it can be shown that the load-deflection response will exhibit a deflection hardening behavior if the fiber potential at the onset of cracking σ_f (i.e., the contribution of the fibers to the tensile strength of the composite) exceeds half of the tensile strength of the matrix σ_t [5].

Therefore, considering the results obtained from back analysis, it is not surprising to get a deflection hardening behaviour in flexion (Figure 10a), even after having a drop in stress after the LOP in direct tension (Figure 10b). This analysis thus illustrates that a non-strain hardening in tension can give a deflection hardening response in flexion.

Durability of the ductile behavior over the time

Due to there is no harmonized testing methods to analyze the durability of these types of sprayed- Ductal® product, Lafarge and CSTB have adopted complementary methods currently applied to fiber-cement flat sheets and GRC. The main results are presented in the Table 2.

Table 2: *Main tensile properties after different treatments*

Conditions	LOP (MPa)	MOR (MPa)	E (GPa)
7d	7,4	15	-
28d	12	22	38
D/W cycle	13.5	19	-
4w Heat	14.5	16.1	30
8w Heat	12.2	14.1	33
16w Heat	13.6	14.4	35
FT cycle	13,5	22	-

CONCLUSION

The spray process has been deeply analyzed to identify the key material's parameters to guarantee an industrial production. Based on that work, the sprayable Ductal® has been developed to fit with rheological and mechanical requirements expected for a Ductal® family product.

The range of sprayed concretes we have developed deliver performances comparable to the range of cast concretes, making this an entirely new solution within the Ductal® product family. In order to guarantee the properties of these new materials to our customers, we are currently working with the French Scientific and Technical Center for Building (CSTB) on a Preliminary Technical Evaluation of Material (ETPM). That will provide a complete characterization of our materials in terms of their mechanical performance and durability indicators. This characterization process will be conducted using elements produced both at the LRC and by our partners, because the elements used must be representative of real-life industrial production.

The industrial production of sprayed Ductal® started in December 2014 to furnish the EDF Campus building closed to Paris (designed by ECDM architectural firm, Mrs Dominique Marrec). 16 different facade elements are produced per days. Each element dimension is about 6m per 3m and 40cm depth. This architectural project in the results of a research started in November 2012 and highlights the new dynamic movement engaged in Lafarge to accelerate innovation and produce “better cities”.

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