New UHPFRC for the realization of complex elements

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Abstract:

Ultra High Performance Fibre Reinforced Concrete (UHPFRC), 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 UHPFRC, such as Ductal®, is booming since few years. Ductal® can be used either as a precast material or cast in-situ, for new constructions or repair and retrofitting. 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 comply with 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 could also be appreciated.

Keywords: Ductal®, spray, glass fibers, rheology, 3D components

1. Introduction

The unique combination of high mechanical strength, self-compacting properties, extreme durability, ductility, and aesthetics make Ductal® a truly revolutionary construction material. Figures 1 and 2 shows several architectural and structural projects in Ductal®, highlighting applications in thin shells and perforated panels.

Figure 1. Examples of structural & architectural projects in Ductal®
(Rabat airport, Casablanca railway station)

Figure 2. Other examples of structural & architectural projects in Ductal®
(Students residence Paris, G8 WAY Washington DC, Mucem museum Marseille, Jean-Boin stadium Paris, Republic bridge Montpellier)

As part of constantly developing the options for manufacturing elements in Ductal®, LafargeHolcim 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 fibre reinforced concrete from Ductal® range suitable for sprayed GRC devices (Glass Reinforced Concrete) has been developed by managing optimization of the packing density to reach mechanical and rheological performance.

2. Background

The spraying technique is used by many precasters because it allows them to create lightweight elements without the need for heavy shuttering that can sometimes cause difficulties. The development of sprayed Ductal® targeted this requirement by focusing particularly on applications that would enable the design of lightweight facades in a range of forms and colors to create architecture consistent with the existing urban fabric.

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. But Ductal® is a self-compacting concrete that flows very easily into shuttering and molds for efficient filling and high-quality finish and texture. To develop a satisfactory wet-mixture for sprayed process, the fresh properties of mortar are controlled to be suitable with the overall process. The right fresh state behavior of sprayed GRC has to be identified. The first step of the research was dedicated to understand the adequate rheology.

The Figure 3 shows the concrete parameters to consider, at each step of the process:

1. **Yield stress above 100 Pa (0.015 Psi).** 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 lack of compaction has to be compensated by the roller. The movement of mortar around the fiber reduces the porosity and consequently increases the adhesion.
3. **Viscosity lower than 23 Pa.s ($3.33\cdot10^{-3}$ Psi.s) at $15s^{-1}$.** The shear-thinning behavior is needed at many steps of the process. The problems induce by a too high viscosity is the incapacity to pump the mortar, high level of rebound of the fibers and finally lack of adhesion between each layers of mortar.

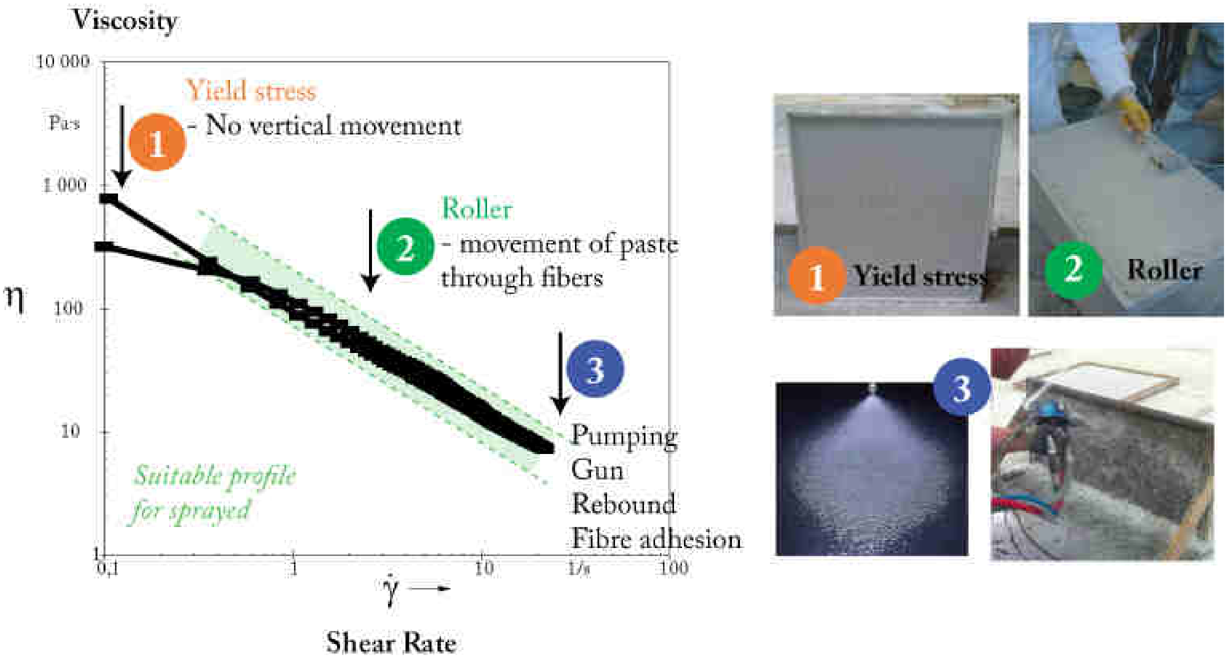

Figure 3. Schematic description of expected fresh state behavior for the GRC process

To understand the works done to develop sprayed Ductal®, a look on the difference of the rheology between the self-compacting Ductal® and the typical GRC is useful (Figure 4). By definition, the main property of a self-compacting Ductal® is to have no yield stress and viscosity remains the same whatever the level of stress applied. But, to reach ultra-high performance, the entire particles skeleton is optimized to reduce as much as possible the porosity. 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-compacting Ductal®. All those observations seem to make incompatible the used of self-compacting Ductal® of vertical sprayed process.

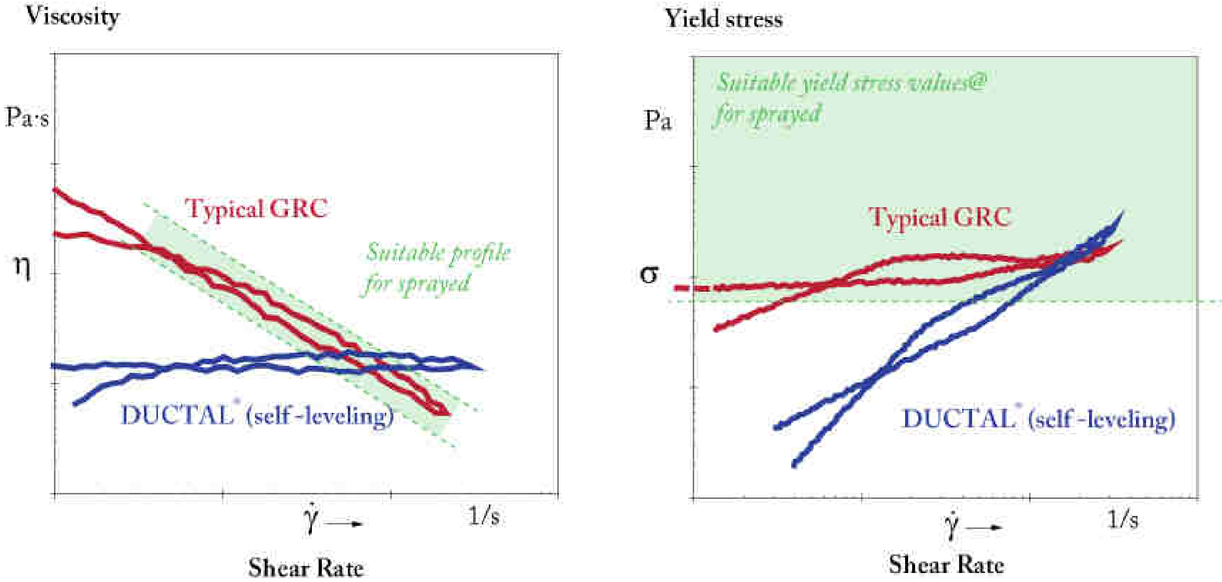

Figure 4. Fresh state comparison between a self-compacting Ductal® and typical GRC

3. Testing Methods

We validated the benefits of the formulations on two different scales. We began on a small scale with an industrial production site set up at the R&D Center with a spray chamber (see Figure 5), pumping system and spray system identical to those used by our customers. We then worked in conjunction with our partner Betsinor, to refine the requirements and reach a full-scale prototype (see Figure 6).

Figure 5. Sprayed setup at R&D Center

Figure 6. Example of 3D panel produced by Betsinor (France)

3.1. Mechanical strengths

Compressive strength, flexural strength, Young's Modulus and shrinkage have been measured according to European standards. The tensile strength is determined from back analysis method of flexural tests.

The sprayable Ductal® was used to produce 700x700x20 mm (27.6x27.6x0.78 in.) large plates. After demolding at 24 hours, 3 specimens measuring 450x145x20 mm (17.7x5.7x0.78 in.) were cut from the large plates for the two directions (longitudinal and transversal). The resulting plates were then placed in a curing chamber at 20°C (68°F) and 100% RH. At 28 days, all 4 plates were tested in four-point bending (see Figure 6), with an inner span of 140 mm (5.5 in.), and an outer span of 420 mm (16.5 in.). With the use of an attached LVDT sensor, the flexural tests were deflection controlled at a constant rate of 0.1 mm/min (0.039 in./min).

Figure 7. Four bending test on a sprayed Ductal® thin plate

3.2. Durability indicators

The approach is based on the choice of a small number of durability indicators which are key parameters for quantifying and predicting concrete durability. These parameters are based on laboratory tests conducted on test specimens or samples: water voids, permeability to oxygen and diffusion coefficient of chloride ions. French standards were used while awaiting publication of the corresponding European norms.

4. Results

Tables 1 and 2 summarize the main characteristic of the sprayed-Ductal® observed under sample produce at the R&D Center and at the Betsinor's plant. Moreover, Table 1 compares some characteristics with a self-compacting Ductal®, commonly used for façade panels.

The performances of this new Ductal® product range are above the existing solutions in GRC industry.

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

Characteristics	Unit	Sprayed Ductal®	Self-compacting Ductal®
Total shrinkage at 90 days	µm/m (10^{-6})	700	900
Compressive strength at 28d	MPa (ksi)	120 (17)	110 (16)
Limit of Proportionality (LOP) at 24h / at 28d	MPa (ksi)	7.0 (1.0) / 12 (1.7)	- / 10 (1.5)
Module of Rupture (MOR) at 24h / at 28d	MPa (ksi)	12 (1.7) / 20 (2.9)	- / 14 (2.0)
Young's modulus at 28d	GPa (ksi)	40 (5800)	45 (6500)
Water porosity of the matrix at 90d	(%)	5 (very high durability)	9 (high durability)
Diffusion coefficient of chloride ions at 90d	10^{-12} m^2.s^{-1} (sq ft.s^{-1})	< 0.2 (2.15) (very high durability)	*similar*
Permeability to oxygen at 90d	10^{-18} m^2 (sq ft)	< 1.0 (10.7) (very high durability)	*similar*

Table 2. Aging effect on the flexural strengths of sprayed Ductal®

Conditions		LOP MPa (ksi)	MOR MPa (ksi)	E GPa (ksi)
Normal (reference)	7 days	7.0 (1.0)	12.0 (1.7)	-
	28 days	12.0 (1.7)	20.0 (2.9)	40 (5802)
Immersion / Drying cycles		13.5 (1.9)	19.0 (2.8)	-
60°C hot water	4 weeks	14.5 (2.0)	18.0 (2.6)	43 (6236)
	8 weeks	14.0 (2.0)	16.5 (2.3)	41 (5946)
	16 weeks	15.0 (2.2)	16.0 (2.3)	42 (6091)
Freeze / Thaw cycles		13.5 (1.9)	20.0 (2.9)	-

5. Discussion

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:

$$\sigma_p = v_f \times \sigma_f \times k \times w \times P_0 \times P_t$$

were ν_f is the volume content of the fibres, σ_f is the direct tensile of the fibres (~1700 MPa / 246 ksi), k is a coefficient taking into account the effect of the fibres orientation in the matrix (typically 0.5, $2/\pi$ or 1 for a 3D, 2D or 1D distribution, respectively), P_0 is the porosity of the bundle, P_t is the portion of monofilaments in the bundle in perfect adhesion with matrix, and ω is a coefficient representing the effectiveness of the fibre/matrix couple (depending on the statistical anchoring length of the fibre with respect to a crack). For the cast solution, assuming k = 0.64 (2D, Figure 8), ω = 0.5 (optimized fibre/matrix anchoring length) P_0= 0.8, P_t= 0.6 (Figure 9) and for ν_f around 5.0%, the estimated upper bound tensile strength of the composite is approximately 13 MPa.

Figure 8. Random orientation of glass fibers after spray

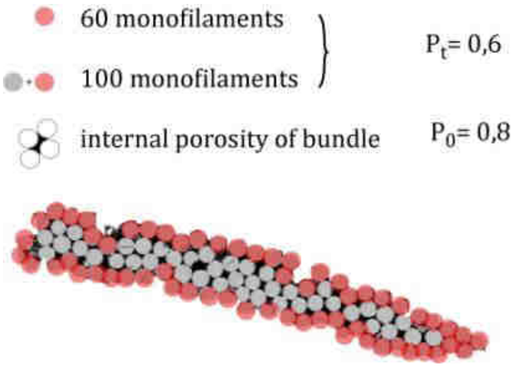

Figure 9. Porosity (in black) of the bundle

To see if the experimental flexural results were consistent with the estimates of the fiber potential outlined above, a back analysis of the flexural results. Considering the relatively homogeneous distribution of cracks along the tensile face in the central section of the specimen, we assume a non-linear homogeneous material, which allows us to define a stress versus strain constitutive equation. Figure 10 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 (1.16 ksi).

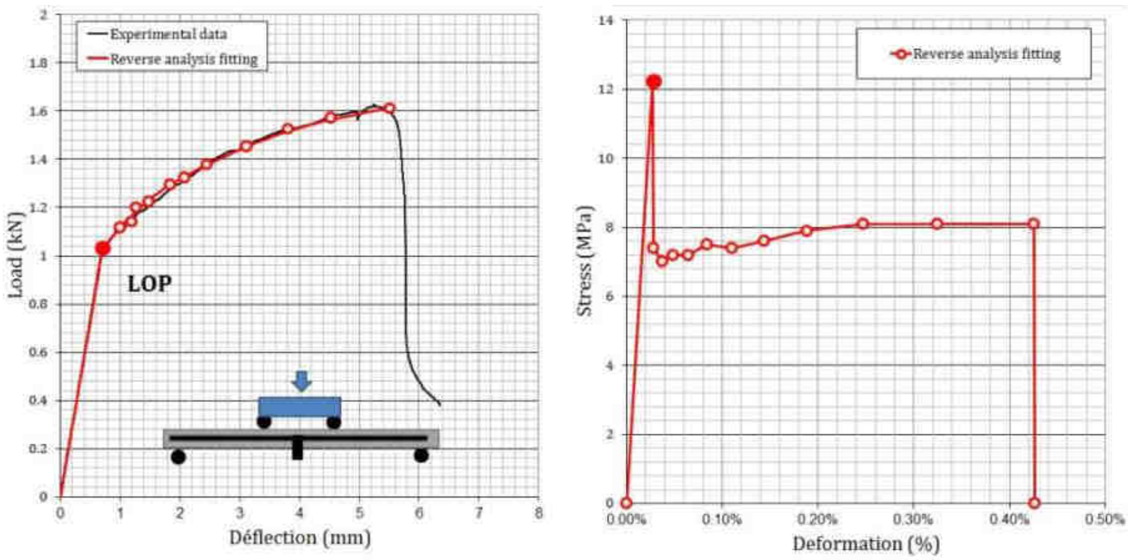

Figure 10. Flexural loading versus deflection curve and Uniaxial tensile stress versus strain curve after back analysis

The influence of the aging effect on the mechanical performances is low, compare to normal GRC. Even if a loss of ductility in bending has been observed, the behavior remains strain-hardening, and so ensures a structural ductility of the elements. A specific design method, based on the Eurocodes framework, has to be developed in order to take into account this ductility at the ultimate limit state. The calibration of the safety coefficients will allow an optimization of the design, by reducing the thickness and minimizing the self-weight.

6. Conclusions

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. A technical assessment has been done on sprayed Ductal® samples, manufactured by Betsinor, to provide a complete characterization of our materials in terms of mechanical performances and durability indicators.

The industrial production of sprayed Ductal® started in December 2014 to supply all the façade panels for the EDF Campus building closed to Paris (Figure 11).

Figure 11. EDF Campus building (designed by ECDM architectural firm, Mrs Dominique Marrec)

7. References

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