SPRAYED UHPC WITH GLASS FIBRES FOR 3D PANELS

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Abstract

Glass Fibre Reinforced Concrete (GFRC) has been developed over the last 50 years into the material it is today and mostly used as a cladding material. The spraying technique is used by many precasters because it allows them to create lightweight elements without the need for heavy shuttering, specifically when the geometry is complex. Nevertheless, the mechanical properties of GFRC have remained relatively low, even with the recent use of new types of admixtures. The weak point of GFRC remains the loss of ductility with time (“aging effect”), especially because of the anchorage degradation of glass fibres. To address this problem, an UHPC (Ultra High Performance Concrete) matrix was developed specifically to make it sprayable with the processes currently used in the GFRC industry. The main challenge has been to get the right rheology (yield stress and viscosity) by maintaining the performances of the UHPC in term of strength and durability.

Résumé

Le composite ciment verre (CCV) a été développé au cours des 50 dernières années pour devenir aujourd'hui un matériau particulièrement utilisé dans le domaine des façades. La technique de la projection est utilisée par de nombreux préfabricants car elle permet de créer des éléments légers sans avoir recours à des coffrages lourds, en particulier lorsque la géométrie est complexe. Néanmoins, les propriétés mécaniques du CCV sont restées relativement faibles, même avec l'utilisation récente de nouveaux types d'adjuvants. Le point faible du CCV reste la perte de ductilité avec le temps ("effet de vieillissement"), notamment en raison de la dégradation de l'ancrage des fibres de verre. Pour résoudre ce problème, une matrice BFUP (Béton Fibré à Ultra hautes Performances) a été spécialement développée afin de la rendre compatible avec les procédés de projection couramment utilisés. Le principal défi a été d'obtenir la bonne rhéologie (limite d'élasticité et viscosité) tout en maintenant les performances d’un BFUP en termes de résistance et de durabilité.

1. GENERAL CONTEXT

Many precasters all around the world use the spraying technique because it allows them to create lightweight elements without the need for heavy formworks that can sometimes cause troubles. The development of sprayed Ductal® targets this requirement by focusing especially 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 main challenge has been to achieve the practical implementation flexibility offered by the spraying technique by designing a sprayed Ductal® solution whose finishing, durability and strength were high according to the definition of UHPC. But up to now, Ductal® is a self-compacting concrete that flows very easily into formworks 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 fresh state behavior of sprayed GRC has to be identified, in order identify the relevant parameters and to define the most appropriate rheology.

2. SPECIFICATIONS OF THE RHEOLOGY

2.1 Parameters

Figure 1 shows the concrete parameters to consider, at each step of the process:

- 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;
- 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;
- 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 is the incapacity to pump the mortar, high level of rebound of the fibers and finally lack of adhesion between each layers of mortar.

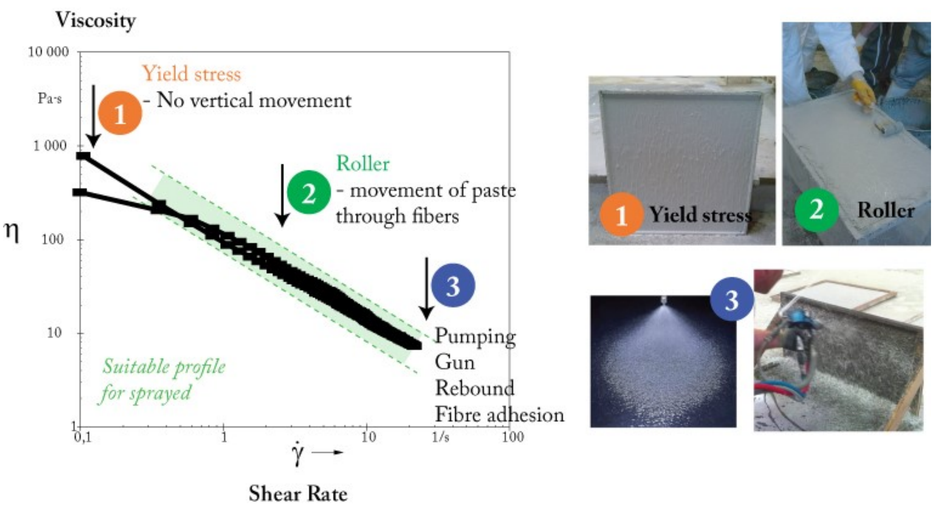

Figure 1: Schematic description of expected fresh state behaviour for the GRC process

2.2 Behaviour

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 2). 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 packing density is optimized to reduce as much as possible the porosity. The counterbalance of this mix-design approach is known as producing materials with a rheo-thickening behavior (apparent high viscosity at high shear rate). The viscosity or thixotropic agents are not suitable 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 promoting yield stress of a self-compacting Ductal®.

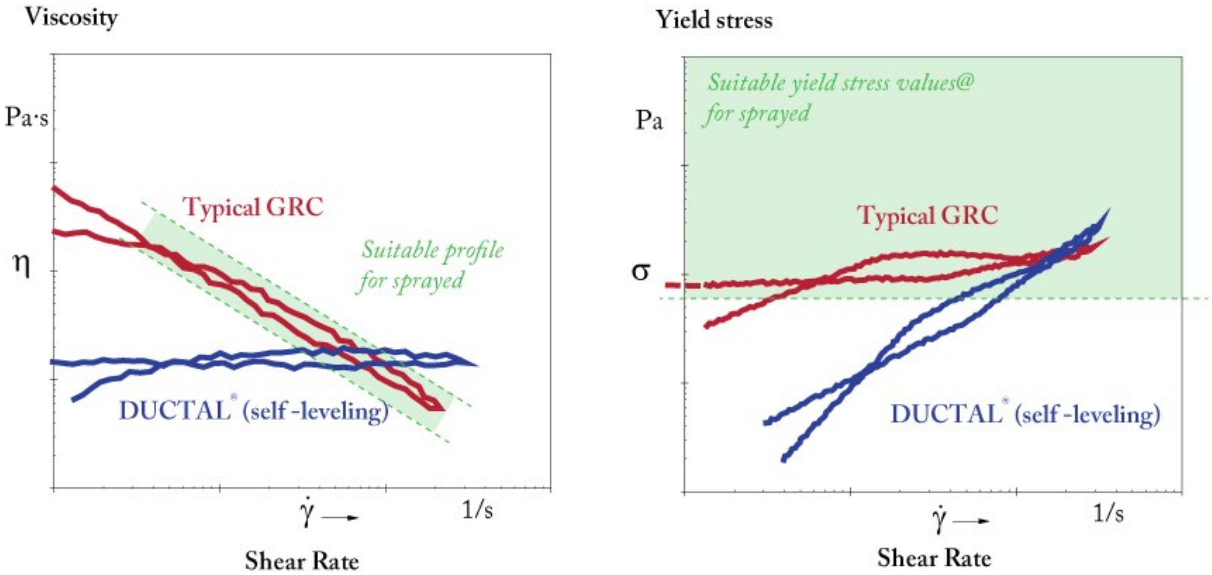

Figure 2: Fresh state comparison between a self-compacting Ductal® and typical GRC

3. CHARACTERISATION

3.1 Samples and prototypes

Figure 3: Sprayed setup at the R&D Center

We validated the benefits of the formulations on two different scales. We started on a small scale (samples) with an industrial production site set up at the LafargeHolcim R&D Center with a spray chamber (Figure 3), 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 (Figure 4).

Figure 4: Example of 3D panel produced by Betsinor (France)

3.2 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 sprayed Ductal® was used to produce 700x700x20 mm large plates. After demolding at 24 hours, 3 specimens measuring 450x145x20 mm 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 and 100% RH. At 28 days, all 4 plates were tested in four-point bending, 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.

3.3 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 OF THE DESIGN TESTS

4.1 Identity card

Tables 1 and 2 summarize the main characteristic of the sprayed-Ductal® observed under sample produce at the LafargeHolcim R&D Center and at the Betsinor's plant. 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®
Total shrinkage at 90 days	mm/m	0.7
Compressive strength at 28d	MPa	120
Limit of Proportionality (LOP) at 24h / at 28d	MPa	7 / 12
Module of Rupture (MOR) at 24h / at 28d	MPa	12 / 20
Young's modulus at 28d	GPa	40
Water porosity of the matrix at 90d	(%)	5 (very high durability)
Diffusion coefficient of chloride ions at 90d	10^{-12} $m^2.s^{-1}$	< 0.2 (very high durability)
Permeability to oxygen at 90d	10^{-18} m^2	< 1.0 (very high durability)

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

Conditions		LOP (MPa)	MOR (MPa)	E (GPa)
Normal (reference)	7 days	7.0	12.0	-
	28 days	12.0	20.0	40
Immersion / Drying cycles		13.5	19.0	-
60°C hot water	4 weeks	14.5	18.0	43
	8 weeks	14.0	16.5	41
	16 weeks	15.0	16.0	42
Freeze / Thaw cycles		13.5	20.0	-

4.2 Back analysis

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:

$$\sigma_p = v_f \times \sigma_f \times k \times w \times P_0 \times P_t \qquad (1)$$

were v_f is the volume content of the fibres, σ_f is the direct tensile of the fibres (~1700 MPa), 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), $\omega = 0.5$ (optimized fibre/matrix anchoring length) $P_0 = 0.8$, $P_t = 0.6$ and for v_f around 5.0%, the estimated upper bound tensile strength of the composite is approximately 13 MPa.

Figure 5: Random orientation of glass fibers

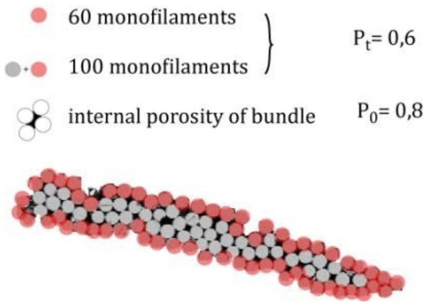

Figure 6: Porosity (in black) of the bundle

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.

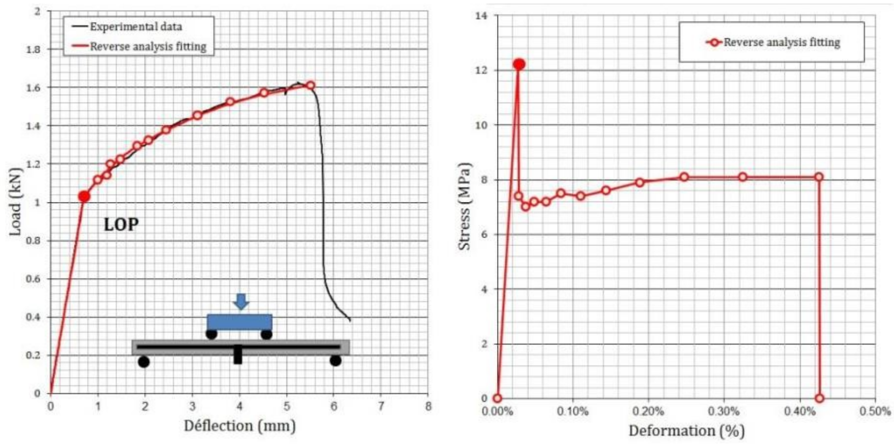

Figure 7: Flexural loading versus deflection curve and uniaxial tensile stress versus strain curve after back analysis

The influence of the aging effect on the mechanical performances is very 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.

5. 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 sprayed 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 near Paris.

Figure 8: View of the EDF Campus building
(designed by ECDM architectural firm, Mrs Dominique Marrec)

Figure 9: View of the sprayed Ductal® facade from outside

Figure 10: View of the sprayed Ductal® facade from inside

REFERENCES

[1] AFGC 2013, "Ultra High Performance Fibre-Reinforced Concretes – Recommendations", Revised edition, June 2013.

[2] Batoz, J.-F., Behloul, M., "UHPFRC development: Experience with Ductal® over the last two decades", *Proceedings of Designing and Building with UHPFRC, State of the Art and Development*, Marseille, France, November 2009, pp. 43–62.

[3] Chen, J. and Chanvillard, G., "UHPC composites based on glass fibers with high fluidity, ductility, and durability", *Proceedings of Ultra-High Performance Concrete and Nanotechnology in Construction*, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials, Kassel, March 2012.

[4] Rigaud, S., Chanvillard, G. and Chen, J., "Characterization of bending and tensile behaviors of ultra-high performance concrete containing glass fibers", *Proceedings of High Performance Fiber Reinforced Cement Composites 6*, Ann Arbor, MI, USA, 2011.

[5] Chanvillard, G. and Corvez, D., "Explicit back analysis method for quick determination of direct tensile strength of plate structural members", *RILEM-fib-AFGC Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete, UHPFRC 2013*, Marseille, France, October 2013.

[6] Chanvillard, G., "Characterization of fibre reinforced concrete mechanical properties: A review, plenary conference", *Fifth International Rilem Symposium on Fibre Reinforced Concretes, BEFIB'2000*, Ed. P. Rossi and G. Chanvillard, Lyon, France, 2000, pp. 29–50.

[7] Zhu, W., Bartos, P. J. M., "Assessment of interfacial microstructure and bond properties in aged grc using a novel microindentation method", *Cement and Concrete Research*, 27(11), 1997, pp. 1701–1711.

[8] Lafarge Ciment, "ETPM Ductal® projeté", *Evaluation Technique Préalable de Matériau du CSTB*, October 2014.