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UPGRADING THE CONCEPT OF UHPFRC FOR HIGH DURABILITY IN THE CRACKED STATE: THE CONCEPT OF ULTRA HIGH DURABILITY CONCRETE (UHDC) IN THE APPROACH OF THE H2020 PROJECT RESHEALIENCE

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Abstract

Current solutions for new concrete constructions in Extremely Aggressive Exposures, as recommended and enforced by design codes, are not taking into account new cement-based construction materials, such as Ultra High Performance Fibre Reinforced Concrete, neither new constituents specifically conceived to improve the concrete durability, because of the lack of standards and technical awareness by most designers and contractors. The H2020 ReSHEALience project will upgrade to the concept of Ultra High Durability Concrete (UHDC), combining nano-scale constituents (nano-cellulose, alumina nanofibers) and self-healing promoters (crystalline admixtures). The paper will present the approach pursued in the project together with a synopsis of the results of ongoing research.

Keywords: Ultra High Durability Concrete, (micro)cracked state, nanoparticles, self-healing.

1. INTRODUCTION

Reinforced Concrete structures exposed to Extremely Aggressive Environments (EAE) experience several durability time-dependent problems, including ageing and corrosion of reinforcement, which may result into the need of early and often continuous repairs. A recent case history analysis [1], showed that 50% of the repaired concrete structures failed once again, 25% of which in the first 5 years, 75% within 10 years and 95% within 25 years. This highlights the urgent need of a profound rethinking of the concept and design processes for new and repaired R/C structures in EAE in view of cost-effectiveness demands. Current solutions as recommended and enforced by design codes, are not taking into account new cement-based construction materials, such as Ultra High Performance (Fibre Reinforced) Concrete - UHP(FR)C, neither new constituents specifically conceived to improve the concrete durability, because of the lack of standards and technical awareness by most designers and contractors.

UHPFRC can be regarded among the most significant innovations in concrete technology introduced in the last twenty years or so. The material concept relies upon a micro-mechanical design of the mix composition, based on the balance between crack-tip toughness and fibre pull-out work [2-4]. Once the first crack is formed, the crack bridging action of the fibres is activated. This results into signature tensile behaviour, characterized by stable multiple cracking process and strain-hardening response, up to the onset of the unstable localization of one single crack [5]. The mix-composition that enables the material to achieve this signature tensile behaviour is characterized by a high binder content and a low water/binder ration, compensated by a high dosage of superplasticizer and results into:

- a superior performance in the fresh state, highly conducive to self-compacting consistency, which may also result into the possibility of tailoring the fibre alignment along the direction of the casting flow and optimize the "in-structure" material performance [6-8];
- a superior durability in the un-cracked state, because of the high compactness of the matrix, as due to the high content of fibres as well as to the use of small aggregates;
- a superior durability in the cracked state, due to the highly effective crack-width control, the penetration of aggressive agents being governed by the width of the single crack [9-10].

Moreover, the synergy between crack tightness and material composition also results into a high conduciveness to autogenous self-healing, with synergetic effects on the enhancement of the material and structural durability [11-24]. Healing products reconstruct the through-crack continuity and also improve the fibre-matrix bond, which may result, when reloading a healed specimen, into the formation of new cracks instead of the re-opening of the healed one [17].

Despite the widely predicated and lab-scale demonstrated benefits that the UHPC/UHPFRC technology is able to bring to the construction sector, its market penetration is still limited. This is due, on the one hand, to the higher inertia of the construction sector in implementing innovation, as compared to other industry sectors, as also due to the "safety of people concerns" embedded in the design and building of each and all building/civil engineering feats as well as to the "uniqueness" of each feat. On the other hand, though some national guidelines are going to be published, UHPFRC still suffers from the lack of internationally recognized testing and design standards, which would provide engineers the required confidence to exploit its multiple benefits in the design and construction of high-end engineering applications. Information is also scant with reference to the durability in the cracked state, which is the true service condition directly affecting the service life of the structure. The methodology proposed by the H2020 project ReSHEALience in order to fill the aforementioned gap will be addressed in this paper.

2. ULTRA HIGH DURABILITY CONCRETE (UHDC): TOWARDS A METAMATERIAL CONCEPT AND A HOLISTIC DESIGN METHODOLOGY.

Improving the durability and extending the service life of structures exposed to EAEs, at the same time reducing their maintenance needs, is an extremely challenging goal which the civil engineering community has to face in the current social and economic framework. The H2020 project ReSHEALience is proposing to upgrade the concept of UHPFRC through the incorporation of tailored functionalities to a "metamaterial" concept, named Ultra High Durability Concretes (UHDCs), which will share the signature tensile "strain hardening" behaviour of UHPFRC.

The ReSHEALience consortium has agreed upon the following definition of UHDC: "strain-hardening (fibre reinforced) cementitious material with functionalizing micro- and nano-scale constituents (alumina nanofibers, cellulose nanofibers/crystals, crystalline admixtures, especially added to obtain a high durability in the cracked state". It is understood that UHDC contains fibres to obtain the strain-hardening response (so it is a FRC, and also a HPFRCC) and it has a special selection of solid particles to achieve the required durability as well as a self-compacting consistency, also instrumental to obtain a homogeneous fibre distribution.

3. TAILORED FUNCTIONALIZATION OF UHDC MIXES: LITERATURE SURVEY AND PRELIMINARY RESULTS

The implemented metamaterial approach to the UHDC concept and design aims to transform the material from a passive provider of protection against degradation into an active player able to govern degradation processes through multi-scale manipulation of the material structure. In order to achieve this goal, three main strategies will be followed, including:

- ***Densification of the matrix***: nano-cellulose fibrils and crystals will be used to improve the density of the Interfacial Transition Zones (ITZs) and compensate autogenous shrinkage.
- ***Crack growth control***: alumina nano-fibres will be used to control the crack initiation phase and different types of micro- and macro-fibres for the propagation phase.
- ***Self-healing***: self-healing admixtures (crystalline admixtures) will be employed to seal small cracks and defects, in case also guaranteeing recovery of material properties.

3.1 Nano-cellulose products

Different nano-cellulose products, including fibrils and crystals, obtained by refining pulps from different sources have been reportedly used in cementitious composites [25], in percentages not higher than 1% by volume. Reported obtained benefits range from increase of compressive and flexural strength [26-29] to reduction of autogenous shrinkage [30].

Microstructural analyses have shown that the obtained improvements are due to two concurrent mechanisms. The first mechanism is the steric stabilization, as confirmed by rheological and heat flow rate measurements and microscopic imaging. The second proposed mechanism, which is likely to be dominant, is referred to as short circuit diffusion, which appears to increase cement hydration by increasing the transport of water from outside the hydration product shell on a cement grain to the unhydrated cement cores. [27].

The ReSHEALience project consortium will employ BioPlus ® Cellulose Nanofibrils (CNF), with dimensions ranging from 5-20 nm in diameter and 500-2,000+ nm in length, and BioPlus® Cellulose Nanocrystals (CNC), with dimensions ranging from 5 nm in diameter and 50-500 nm in length (Figure 1) supplied in sonicated suspension at 10% solid content.

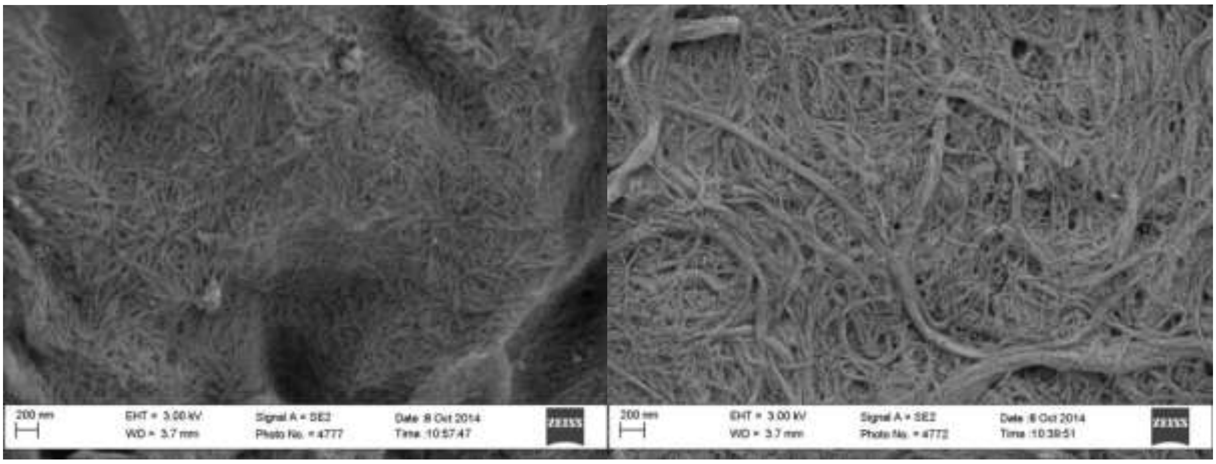

Figure 1: Bioplus ® cellulose nanocrystals (left) and nanofibrils (right).

3.2 Alumina nanofibers

In the literature, the use of alumina Al_2O_3 nano-particles, employed at dosages varying from 0.5% to 1%, is reported to improved strength and reduced setting time, as a results of more compact microstructure. A lower strength decay after exposure to high temperature was also reported [31] as well as an improvement in freeze-thaw resistance [32].

The aluminium oxide nanofibers branded as NAFEN™ , which will be employed in the current project, have been so far applied into a broad range of industrial products (aerospace, automotive, energy), resulting into a confirmed 20-50% improvements in mechanical properties of polymer and composite end products. The fibres are 4 to 11 nm in diameter and from 100 to 900 nm long, with a specific surface equal to 155 m^2/g [Figure 2]. In order to be employed into a cementitious composite mix featuring low w/b ratios they need to be supplied into a sonicated suspension at a solid concentration ratio equal to 10%, much higher than for other applications.

Preliminary investigation has been performed at University of Wisconsin at Milwaukee, with reference to a typical UHPC matrix, with NAFEN fibres dosed at 0.25% by weight of cement, and in case with 1% addition of either meta-kaolin or silica-fume. The results have shown a roughly 30% increase of both 7 and 28 days compressive strength. The same improvements are confirmed also when different fibres (12 mm long) have been added (Figure 3).

3.3 Crystalline admixtures

Though Crystalline Admixtures, are well known and widely used in modern concrete technology, being classified as a special type of permeability reducing admixture, they have only recently started receiving special attention as self-healing promoters. Significant amount of work in this respect has been done [33-38]. Moreover, an interesting synergy with the dispersed fibre reinforcement has been observed [39 – Figure 4a-b], in the case of a UHPFRC mix (w/b ratio 0.18) containing 0.8% by cement weight of Penetron Admix ® and 100 kg/m^3 straight short steel fibres (l_f/d_f = 13/0.16). The filling of the cracks by crystalline healing products is likely to activate a sort of chemical pre-stressing throughout the cracked material, from which the healing induced recovery of the performance is likely to benefit to a greater extent than in the case of ordinary FRC and plain concrete. A contribution in this sense may also come from the light shrinkage-reducing effect that the admixtures may provide, as from preliminary results shown in Figure 5.

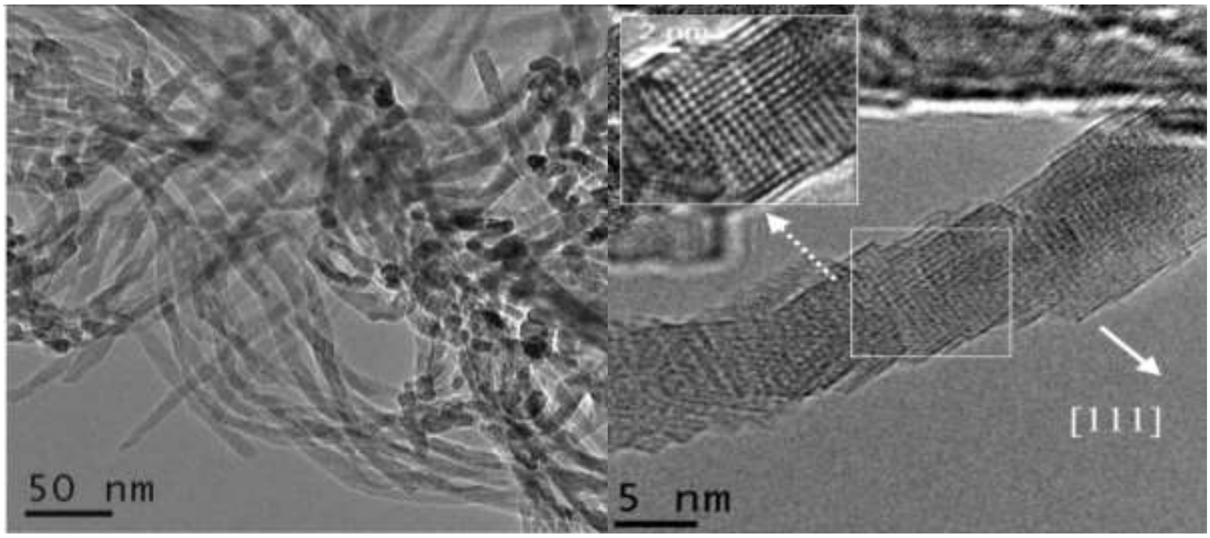

Figure 2. NAFEN® aluminium oxide nano-fibres at different magnification scale.

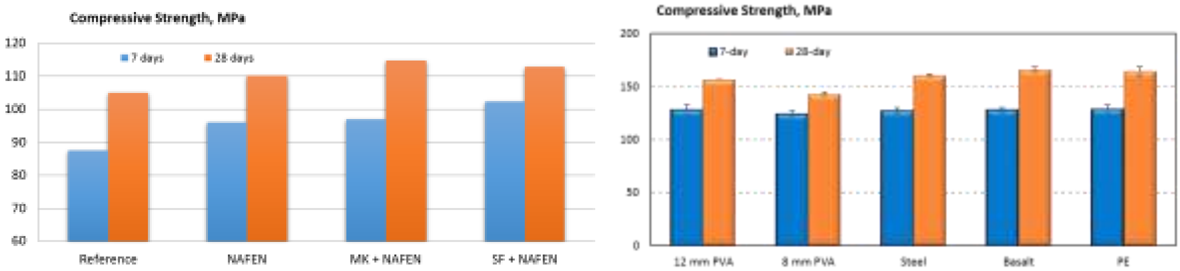

Figure 3. Effect of NAFEN™ fibres on the compressive strength of UHPC mortars (left) and effect of fibres on compressive strength of UHPC mortars with NAFEN ™ fibres (right).

The research activity performed in the framework of the project is going to further investigate this issue, so far limited to the results of a tailored experimental campaign, also with reference to the EAE of interest as well as to the synergy between the employed crystalline admixture and the selected nano-scale constituents detailed above.

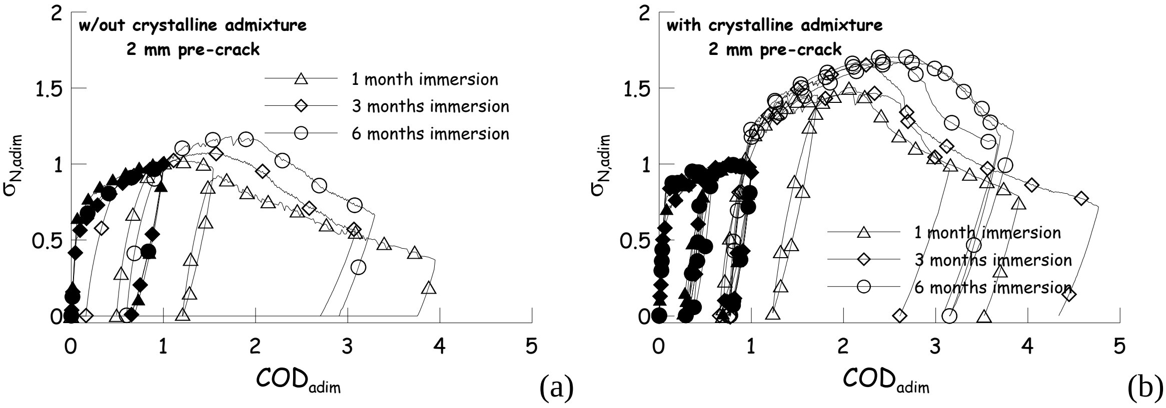

Figure 4. Crack-healing induced recovery of mechanical properties (4point bending) in UHPC specimens without (a) and with (b) crystalline admixture cured in water after cracking [52].

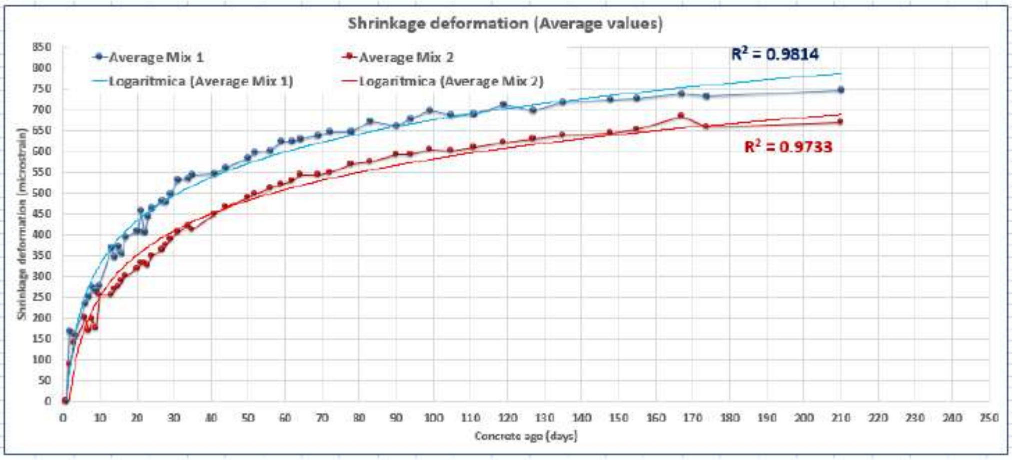

Figure 5. Effect of crystalline admixture (0.8% by cem weight Penetron Admix ®) on free drying shrinkage in FRC mix (0.45 w/c ratio)

4. CONCLUSIONS

The main objective of H2020 project ReSHEALience is to upgrade the concept of UHPC to Ultra High Durability Concrete (UHDC). The underlying key idea is to transform, through the incorporation of self-healing stimulators and nano-constituents, the material from a passive provider of protection into an active player, able to respond to degradation processes as a function of the durability requirements. The self-healing functionalization, with continuous tailored recovery of performance achievable on demand, will reduce the need of repair actions and the global cost, which will compensate the higher initial material cost (Figure 6). This will result into a breakthrough metamaterial concept in which durability is not a bonus but becomes the governing objective, able to "convert" cement-based construction materials from "durability passive" spectators with structural functions, into active players, using value-added synergy-acting functionalities "tailored" to an as broad as possible range of applications.

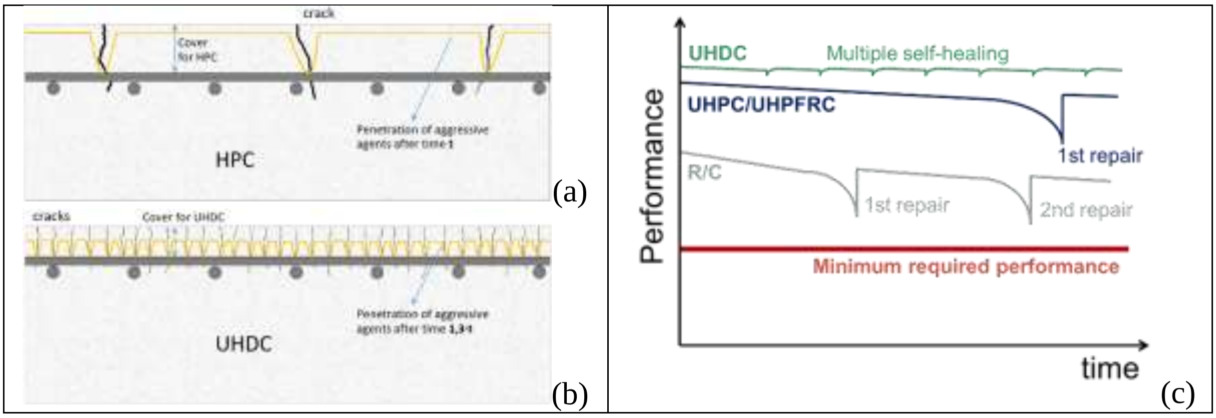

Figure 6. Concept of HPC and UHDC (a-b) durability in performance/repair/time frame (c).

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