An Overview on H2020 Project “ReSHEALience”

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Abstract

In the framework of H2020, the European Commission recently funded the project ReSHEALience (www.uhdc.eu). The main idea behind the project is that the long-term behaviour of structures under extremely aggressive exposure conditions can highly benefit from the use of high performance materials, in the framework of durability-based design approaches. The project consortium, coordinated by Politecnico di Milano, features 14 partners from 8 different countries, including 6 academic/research institutions and 8 industrial partners, covering the whole value chain from producers of concrete constituents to construction companies to stake-holders and end-users. The main goals of the project are the development (a) of an Ultra High Durability Concrete (UHDC) and (b) a Durability Assessment-based Design (DAD) methodology to improve structure durability and predict long-term performance under Extremely Aggressive Exposures (EAE). The project will tailor the composition of UHDC, by upgrading the UHPC/UHPFRC concept through the incorporation of tailored nanoscale constituents.

Keywords: Ultra High Durability Concrete (UHDC); Durability Assessment-based Design (DAD); modelling; green energy; Blue Growth; heritage conservation.

1. Introduction

Reinforced concrete structures under marine and chemical attack exposures (XS and XA) experience several time-dependent durability problems, which require early and often continuous maintenance. Typical pathologies in structures under XS and XA conditions consist of excessive corrosion, accompanied by cracking and spalling of concrete cover. Moreover, under acid attack the dissolution of the cement paste is the main depredated action, followed by the attack of non-stable (e.g. calcareous) aggregates. The progressive dissolution of the cement paste promoted by the acidification, as well as the precipitation of expansive salts penetrating into the porous matrix can contribute to the damage and cracking of concrete.

A case history analysis provided by the CON-REP-NET project [1] showed that 50% of the repaired concrete structures failed again, 25% of which in the first 5 years, 75% within 10 years and 95% within 25 years. There is hence an urgent need of profoundly rethinking the concept and design of new and repaired R/C structures in aggressive environments, in view of cost-effectiveness demands.

Current solutions for new concrete constructions in extremely aggressive exposure (EAE) conditions, as recommended and enforced by design codes, are not taking into account new cement-based construction materials, such as Ultra High Performance (Fiber Reinforced) Concrete (UHPC/UHPFRC), neither new constituents to improve the durability (including nanoparticles or self-healing promoters), because of the lack of standards and of technical awareness by most designers and contractors. This category of new advanced cement-based materials will lead to a lifetime increase for structures in aggressive environments, with lower degradation rates than high performance R/C used in current solutions, for both new constructions and structures already suffering initiated degradation, including corrosion of reinforcement, and hence needing repair.

The use of UHPC/UHFRC still has significant limitations to be overcome and the material has so far failed to stand as the market breakthrough concept/product it was expected to be. This is due to

the claimed superior durability of UHPC/UHPFRC, which has been almost exclusively proven in the laboratory, and with main reference to the uncracked state. With reference to the cracked state, a “superior durability” is generally heuristically justified because of the higher crack tightness characterising the material response under tensile loads. Moreover, its use has hardly been accompanied by design considerations, due to the lack of internationally recognized regulations, and a clear quantitative evaluation of the structure lifespan or service life is so far also lacking.

In current design approaches, lifespan is defined by a target reference value, which, through a “structural class concept” and as a function of the exposure class, results into prescriptions deemed to guarantee the demanded level of durability. These prescriptions imply the use of high cement content, low water/cement ratios, suitable aggregates, high reinforcement covers, and also the use of new types of corrosion-resistant reinforcement (like, for instance, epoxy-coated, stainless/galvanised steel or polymer bars). All the above results into a non-economic and non-optimal structural design, since the overall member dimensions and the material structural efficiency are impaired by the high cover thickness.

The EC H2020 funded ReSHEALience project (www.uhdc.eu) moves from the consideration that the long-term behaviour of structures under EAE conditions can highly benefit from the use of high performance materials, in the framework of durability-based design approaches. The project will develop an Ultra High Durability Concrete (UHDC), by upgrading the UHPC/UHPFRC concept through the incorporation of tailored functionalizing constituents, including alumina nano-fibres, bio-based nano-cellulose and crystalline admixtures, upgrade experimental methods to validate its durability in service conditions, and develop a theoretical model to evaluate ageing and degradation of UHDC structures in order to predict their lifespan. New design concepts will be proposed and validated through long-term monitoring in six full-scale proofs-of-concept, selected as representative of cutting edge economy sectors, such as green energy, Blue Growth and conservation of R/C heritage.

2. From current practice to UHPFRC: an asset for enhanced durability

Durability is recognized as a design target requisite by current international design codes on reinforced concrete structures [2-4]. Nonetheless, recommendations and prescriptions therein provided are far from constituting a true durability performance-based design approach as a whole. In current design approaches, lifespan is defined by a target reference value, which, through a “structural class concept” and as a function of the exposure class, i.e. environment aggressiveness, results into prescriptions deemed to guarantee the demanded level of durability. These prescriptions concern measures such as water/cement ratio and type of cement, minimum cover to reinforcement, maximum allowable crack widths and specific criteria, including, e.g., the use of galvanized/stainless steel. While EN1992-1-1 contains dedicated prescriptions for minimum cover under XS exposure, no specific considerations are addressed for the minimum cover in the case of structures under chemical attack (XA), though EN 206-1 recommends special attention to be given to the cement type and concrete composition (e.g. sulphate resisting cement for XA2 and XA3). Also for cracking limit states specific prescriptions referring only to XS exposure can be found in the codes.

In order to satisfactorily address higher durability requirements together with the surging demand for structures and infrastructures facilities to be built or renovated, the concrete technology sector has been providing a wide variety of concepts and products in the last twenty years.

Incorporation of dispersed fibre reinforcement into a cementitious matrix is a consolidated technology which results into a composite material, known as Fibre Reinforced Concrete (FRC), already incorporated in the fib Model Code 2010, which features enhanced post-cracking toughness i.e. capacity of sustaining tensile stresses even after a crack is formed and upon its continuing propagation. This capacity results in a better control of the crack opening, i.e. under the same stress level a lower individual crack opening is expected, which improves the durability performance as well, since the penetration of

aggressive agents is promoted by larger cracks and conversely is reduced by narrower cracks.

The FRC concept has been upgraded to Ultra High Performance (Fiber Reinforced) Concrete (UHPC/UHPFRC) by designing the material in the cracked state through micromechanics-based considerations [5]. The objective is to obtain multiple cracking and strain hardening behaviour, so that the same level of damage is not concentrated into the opening of a single crack but is spread into several cracks, each one of them opened up just a few tens of microns. This brings further improvement of durability which goes hand in hand with the improvement of the tensile mechanical behaviour. Such a micromechanically-designed composition results in a very dense microstructure, which prevents the penetration of aggressive agents into the bulk material, and so slows down the mechanisms of deterioration. However, few studies have focused on the durability of these materials in the cracked state, which is the true service condition directly affecting the lifespan of structures, and hardly any approach for quantifying durability parameters in the cracked state does exist. Additionally, scant information is available on the effects of aggressive environments on the mechanical properties.

Despite this lack of information, structures made of or strengthened with UHPC/UHPFRC show excellent performance in several field applications, from the first UHPFRC pedestrian bridge built in Canada in 1997 to several other examples (mainly bridges but also retrofitting) in Canada, France, Germany and Spain. The Oveja’s Ravine Footbridge in Alicante (Spain) built in a XS1 exposure is worth a special mention. Nonetheless, internationally accepted design recommendations do not exist for this class of materials, though national recommendations have been already published, e.g. in Australia and France. Besides this, most of the applications built so far have dealt with landmark infrastructure feats (bridges) for which no problem existed in sustaining the significantly higher cost of a high performance material. Often proprietary products were used, regarded as a sort of “luxury”, which has hindered, and still does, a wider market penetration of this “material concept”.

3. Towards a metamaterial concept and a holistic design methodology

The improvement of durability and reduction of maintenance efforts is of the utmost importance for structures in extremely aggressive environments. The challenge needs to be tackled through a “holistic approach”, which encompasses the concept and development of advanced materials and tailored design approaches to provide innovative structural solutions aimed to provide fit-for-the-purpose answers to the needs highlighted above. To achieve the required improvements in durability, the concept of Ultra High Performance (Fibre Reinforced) Concrete (UHPC/UHPFRC) will be upgraded to a “metamaterial” concept, through the incorporation of tailored functionalities to enhance the long-term durability performance. Through this approach, a new category of advanced cement based materials, named Ultra High Durability Concretes (UHDCs) will be

achieved. UHDC is defined as “a strain-hardening (fibre reinforced) cementitious material with functionalizing micro- and nano-scale constituents especially added to obtain a tailored durability in the cracked state”. Current experimental tests, numerical models and engineering design approaches are not optimized to fully exploit the whole set of potentials brought by these categories of advanced cement based materials. In order to fill this gap, the ReSHEALience project will work on adapting/improving existing testing techniques and design criteria or formulating and validating new ones, so that they can be effectively and reliably applied to UHDC.

The formulation of UHDC will be conceived in the framework of a “metamaterial concept approach” aimed at achieving fit-for-the-purpose properties, which are normally not achieved through conventional cement based material composition, by exploiting synergies from the incorporation of tailored nano- and micro-scale constituents. These

Figure 1. Modelling workflow

are deemed to act at the molecular level of the material structure providing its functionalization to the achievement of the desired properties and levels of performance. UHDC developed and used in the ReSHEALience project will share the signature tensile “strain hardening” behaviour of UHPC/UHPFRC, thanks to a load bearing capacity provided by the fibre reinforcement, which is greater than the cementitious matrix cracking strength. Moreover, the special properties of UHPC/UHPFRC, and hence of UHDC, compared with traditional concrete, makes it essential to define new experimental tests or modify the existing ones, which included assumptions of mechanical behaviours that were not consistent with strain-hardening concretes.

The incorporation of nanoparticles for material functionalization [6,7], together with the use of self-healing additions [8,9], are promising solutions to produce more durable cementitious composites, extending the service life of structures and reducing maintenance costs and repair efforts. Though several studies have been published on these solutions, mainly related to lab-scale investigations, the long-term durability properties in real conditions have not been evaluated so far. The exploitation of nanotechnology in concrete on a commercial scale remains limited with only few results converted into marketable products. Nano-engineering and the use of nano-particles can be used to tailor and add multiple functionalities to concrete, to enhance either mechanical or durability behaviour, or both. This would be achieved by incorporating new properties such self-healing capabilities, high ductility, and self-control of cracks. Benefits from the use of different kinds of nanoparticles have been mostly addressed at the laboratory scale, with limited or no scalability of the production to meet the requirements of large scale applications. As for the self-healing, UHPC/UHPFRC contains high content of cement, with low water/cement ratio, which leaves significant quantities of cement un-hydrated. This, together with high fibre dosages which restrain the crack width, makes the material highly conducive to exhibit autogenous healing capacity. Crystalline admixtures (CA), classified as a special type of permeability reducing admixture, have

received special attention as self-healing promoters, due to their availability and use in the construction industry. Improvement of properties has been demonstrated at lab level, with better improvements when used in UHPFRCs. The scalability of these finding to large scale applications has hence to be promoted, together with the definition of standard methodologies for evaluating self-healing effects or assessing the effectiveness of self-healing technologies [10].

In the same framework, experimental characterization of the UHDC durability will couple adaption of conventional test methodologies with one-of-a-kind techniques (neutron radiography, X-ray computer tomography, and nano-indentation) with the aim of bringing the level of investigation down to the intrinsic structure of the material. This will allow understanding how the functionalizing constituents are able to affect the nature and kinetics of the processes governing the long-term material behaviour, also in the sight of formulating and validating predictive models, which only can allow the assessment of the structure durability in real scenarios. This is quite a challenging task, involving non-conventional experimental capabilities and most of all requiring the investigation to span along a time frame whose extent could hardly match with the needs of a market oriented technology transfer.

Durability models existing in the literature are limited to one or two of the several different mechanisms which govern degradation and ageing and hence the durability of cement-based materials see, e.g., [11]). The modelling activity in ReSHEALience will move from the description of aging and degradation of UHDC to predict the service-life of UHDC applications under EAE conditions. Multi-physics continuum tightly coupled models, taking into account both the aggressiveness of the environment and self-healing of UHDC, will be combined into an overall numerical code and applied to macroscale phenomena. The model will link the effects of chemical reactions, transport of ions, moisture and heat, in cracked and un-cracked concrete conditions, corrosion, damage initiation and propagation in reinforced concrete at macroscale (Figure 1) [12-14]. As a main advantage, the model can be employed not only to support the

experimental results of the project but also to simulate the behaviour of real structures in service conditions. Necessarily limited experimental and simulation raw data, which stand as the basis for durability modelling, can be treated using fuzzy-probabilistic strategies [15-17]. This mathematical strategy has proven efficient for SHCC and chloride ingress but is open for application to other types of cement-based composites as well as for further and multiple exposures and degradation mechanisms.

The global sustainability performance of the developed materials and structural solutions, as compared to traditional ones, will be assessed in a cradle-to-cradle approach through Life Cycle Analysis combined with evaluation of economic viability (Life Cycle Cost – LCC) and social acceptance (Social Life Cycle Analysis – SLCA),

considering material composition, embodied energy, potential waste, durability improvement over the whole life cycle and including impact of deconstruction and recycling.

4. Advance with respect to the state of the art

The activities of the project will find their successful completion in the design, construction and monitoring of six real scale prototypes, including a cooling tower water basin and a geothermal mud collection basin based in Italy, a floater for off-shore wind turbine and a mussel-raft to be installed in the Mediterranean sea offshore from the Valencia coast, a precast breakwater elements to be installed along the British Isles coast and the retrofitting of a severely damaged water tower in the Valletta Grand Harbour region in Malta. The choice of the type

Figure 2. Concept of project ReSHEALience and TRL advancements

and location of the pilots is innovative, as they encompass several cutting-edge economical activities, from green energy production to activities linked to Blue Growth and conservation of reinforced concrete architectural heritage. They also represent real design challenges fully focused on the scope of the call. The involvement of precast companies, which will adapt their production lines to the use of the new UHDC technology, will already imply the possibility of series large scale manufacturing of the same “pilots”, to be employed for multiple installations. This will pave the way and foster the achievement of a level equal to Technology Readiness Level TRL6, and in some cases even to TRL7, for these typologies of intended applications (Figure 2). The on-site performance of pilots will be continuously monitored employing tailored non-destructive methodologies and purposely developed innovative sensors.

5. Conclusions

The ReSHEALience project aims at providing an answer to the needs of structures exposed to extreme aggressive environmental conditions through an innovative material concept and a tailored durability-based holistic design approach. The use of specific types of UHDC is a promising way to enhance the long-term durability behaviour in the micro-cracked state.

The need of repair actions and the global cost will be reduced, to compensate the higher initial material cost, thanks to the self-healing functionalization, with continuous tailored recovery of performance achievable on demand, of UHDC. The use of UHDC, meant as a driver to this conceptual design approach, will advance the current state of knowledge and practice and improve the structure service life through:

- a breakthrough durability-based material concept and design in which durability is not a bonus (as it currently is for UHPC/UHPFRCs) but becomes the governing objective.
- a robust durability evaluation and modelling activity in real service conditions, to identify and quantify the parameters to be used in a durability-based design and their threshold

values, and for monitoring the evolution of these parameters in the real structure.

- a holistic design approach, which moves from the material to the structural durability, to quantify the resulting increase in the service life of structures made of UHDC, and the related outcomes in terms of LCC and SLCA.

The interdisciplinary concept of the project, which comes from specific needs highlighted by the stakeholders to solve problems of non-efficient use of resources in selected applications, will move from a prescription- to a performance-based material and structural durability concept, also meant as a driver of research, innovation and development. The proposed DAD approach for the design and assessment of UHDC structures aims at the breakthrough target of the overall resilience of the engineering application. This encompasses material robustness, structural and material redundancy and resourcefulness and rapidity.

Finally, the demonstration provided through six different pilots (designed, built and monitored even after the project end, under real site conditions) will testify to the true performance of materials, products and structures as a whole. The participation of engineering companies will give a first-hand view of the problem to the research partners. This focus of the project involving public and private partners from different specialties is the way to successfully tackle the challenge.

6. Acknowledgements

The ReSHEALience project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 760824. The information and views set out in this publication do not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.

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