EXPERIMENTAL CHARACTERIZATION OF THE TENSILE CONSTITUTIVE BEHAVIOUR OF ULTRA-HIGH PERFORMANCE CONCRETES: EFFECT OF CEMENT AND FIBRE TYPE

Francesco Lo Monte (1) *, Eduardo J. Mezquida-Alcaraz (2), Juan Navarro-Gregori (2), Pedro Serna (2) and Liberato Ferrara (1)

(1) Politecnico di Milano, Milan, Italy

(2) Universitat Politècnica de València, Valencia, Spain

* Corresponding author: francesco.lo@polimi.it

ABSTRACT

The Research Project ReSHEALience has been launched in 2018 in the framework of the European Programme Horizon 2020. The project aims at developing a new approach for the design of structures exposed to extremely aggressive environments, based on durability and life cycle analysis. In this regards, the starting point is represented by new advanced Ultra-High Performance Fibre Reinforced Cementitious Composites (UHPFRCCs), called Ultra-High Durability Concretes (UHDC) because of their enhanced durability obtained by means of engineered composition, which should be characterized by strain hardening behaviour under tension in both ordinary and very aggressive conditions. In this context, the first step is to develop an effective approach for identifying the main parameters describing the overall behaviour in tension. In the present study, indirect tension tests have been performed via 4-Point Bending Tests (4PBT). Starting from the test results, a combined experimental-numerical identification procedure has been implemented in order to evaluate the effective material behaviour in direct tension in terms of stress-strain law. Finally, the comparison among three mixes differing for fibre and cement type is reported in terms of tensile response and post-crack localization behaviour.

KEYWORDS: ReSHEALience, Ultra-High Durability Concrete – UHDC, tensile constitutive behaviour, identification.

1. INTRODUCTION

In the present study, the mechanical characterization in tension of three Ultra-High Performance Fibre-Reinforced Cement Composites (UHPFRCC) is reported as a result of the application of a combined experimental-numerical approach aimed at the identification of the constitutive tensile behaviour. This is instrumental for the development of cementitious composites with improved durability, in which the interaction of reduced crack-opening (thanks to fibre-triggered multiple cracking) and engineered self-healing is exploited for significantly increasing the long term performance in aggressive environments.

This is the first step of the Research Project ReSHEALience, launched in 2018 and involving 14 Partners and 3 linked third parties all around Europe, within the challenging framework of the European

Programme Horizon 2020. The main objective is to develop a durability-oriented structural approach for both ordinary and extremely aggressive environments, based on the concepts of Durability Assessment based Design (DAD) and Life Cycle Analysis (LCA).

In parallel to the development of cementitious composites with enhanced durability, a new design approach is under development in which, via the explicit evaluation of key durability parameters, the inherent features and advantages of these advanced materials can be fully exploited [1]. The consistency of the developed approach is now under verification thanks to the survey of 6 full-scale demonstrators, which have been designed and realized according to the above-mentioned Durability-Based Design and are monitored in time in terms of different key performance indicators. Finally, advanced numerical models will help in generalizing the results within a practitioner-friendly framework.

Hence, 3 UHPFRCCs with engineered self-healing capability have been formulated (also called UHDCs in the following [2]) in order to choose the optimal solution. The composition of the mixes is based on the rather established knowledge about UHPFRCC. In particular, fibres are instrumental for obtaining a hardening behaviour in bending and even in direct tension, thanks to the multiple stable crack propagation following the onset of the first crack, till localization of a single unstable propagating crack occurs [3]. This allows for limiting crack opening even for significant tensile deformation by balancing crack-tip toughness and fibre pull-out work [4-6]. In the present case, a combination of cement and slag, small aggregates (maximum size of 2 mm) and structural fibres at dosages higher than 1.5% by volume is adopted.

Self-healing, together with the extensive multiple cracking characterized by very small crack openings, makes it possible to significantly increase the durability of these cementitious composites in the cracked state, which is the ordinary service-life condition of concrete structures [7-13].

In this context, stress-strain law identification in direct tension is of primary importance for the generalization of the results, and a few approaches can be found in the literature [14-20]. This task is, however, not trivial, due to the inherent redundancy of the most common adopted indirect tests such as 4-Point Bending Test - 4PBT (see also [21]).

In the present paper, the approach developed for the characterization of the tensile “constitutive” behaviour of three UHDCs (namely UHPRCCs with improved durability) and for the identification of the main mechanical parameters is described. The approach is based on a combination of 4PBT and inverse analysis. The procedure described allows for the estimation of the constitutive law in direct tension starting from indirect tests.

2. EXPERIMENTAL PROGRAM

2.1. Concrete mixes

The reference UHDC mix (XA-CA) contains 600 kg/m^3 of cement (CEM I 52.5), 500 kg/m^3 of slag, 982 kg/m^3 of sand with a maximum aggregate size of 2 mm and 120 kg/m^3 of straight steel fibres (l_f / d_f = 20 / 0.2 mm). After mixing the solid parts, 200 l/m^3 of water are introduced together with 33 l/m^3 of superplasticizer. Penetron Admix®, in the content of 0.8% by cement mass, is also introduced, whose effect on the overall performance of concrete mixes has been investigated elsewhere [22,23]. In mix XA-CA-Amf, steel fibres are replaced with 111 kg/m^3 of metallic amorphous fibre (l_f / w_f / t_f = 15 / 1 / 0.024 mm), while in mix XA-CA-CEMIII, CEM I is replaced with CEM III.

The constituents’ proportions of all mixes are reported in Table 1.

For each mix, six 100x100x500mm^3 prismatic beams have been cast. Further studies on the same mixes can be found also in [24,25].

2.2. Test setups and specimen geometries

The mechanical characterization has been performed via 4-Point Bending Tests (4PBT) on un-notched beams (l·w·h = 500x100x100mm^3). 4PBT on un-notched specimens is adopted since it allows to investigate multiple cracking in the central region L_o, where bending moment is constant.

During the test, (a) the relative vertical displacement of the mid-span section with respect to the supports and (b) the Crack-Opening Displacement – COD across the central region of the specimen are monitored via two LVDTs each, as represented by red segments in Figure 1.

Horizontal LVDTs have been fixed to metal platelets, which were glued in the positions reported in the figure, while vertical ones are mounted to an aluminium frame simply supported on the two ends of the specimen. More complex arrangements of transducers could be also employed in order to better determine the crack localization point [20]. In the present study, the tests were stroke-displacement controlled. All tests were performed after at least 90 days from casting, in order to allow slag to develop the maximum possible long term hydration and pozzolanic activity, as compatible with the low water-to-binder ratio employed.

In the curing period, all samples were stored in climate chamber (R.H. = 90%, T = 20°C).

Table 1. UHDCs' mix compositions.

Constituents [kg/m^3]	**XA-CA**	**XA-CA-Amf**	**XA-CA-CEMIII**
CEM I 52.5	600	600	-
CEM III 52.5	-	-	600
Slag	500	500	500
Water	200	200	200
Steel fibres	120	-	120
Amorphous fibres	-	111	-
Sand (0-2 mm)	982	982	982
Superplasticizer	33	33	33
Crystalline adm.	4.8	4.8	4.8

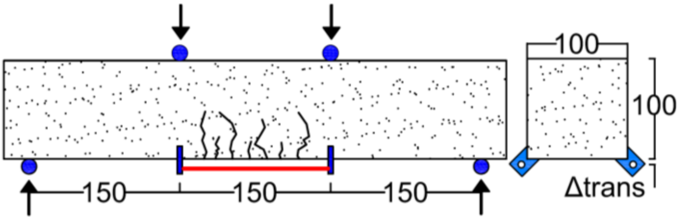


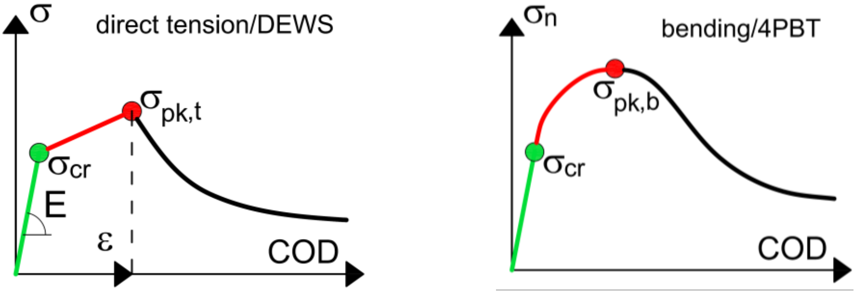
Figure 1. Scheme for 4PBT on small un-notched beams.

3. IDENTIFICATION OF THE MECHANICAL PARAMETERS IN TENSION

The typical behaviour in direct tension and in bending in case of strain-hardening materials is reported schematically in Figure 2. For both direct tension and bending, there is an initial perfect elastic branch which ends when the first crack occurs (at $\sigma = \sigma_{cr}$). After that, in softening materials, localization occurs and load decreases.

In the case at issue, on the other hand, the amount of fibre allows for increasing the external load after first crack is formed, this being related to the concept of hardening. This is made possible by the bridging-effect of fibres crossing the cracks.

Finally, crack localization occurs (at $\sigma = \sigma_{pk,t}$ in direct tension and at $\sigma = \sigma_{pk,b}$ in bending) and the further tensile deformation concentrates into a single crack with the macroscopic effect that external load starts decreasing. It is worth noting that in the general case $\sigma_{pk,b} >> \sigma_{pk,t}$.



(a) (b)

Figure 2. Schemes of σ_n – COD curves (a) in tension and (b) in bending.

The evaluation of σ_{cr} and $\sigma_{pk,t}$ (and of the correspondent strains) is of primary importance, since they describe the multiple cracking stage. When starting from bending tests, however, such parameters can be identified just by means of a careful back analysis, due to the rather smooth transition among the elastic, the hardening and the softening branches. This is caused by stress redistribution across the specimen depth under bending.

Hence, the estimation of the mechanical response in direct tension needs a combined experimental-numerical approach. In particular, after performing the flexural tests, the inverse analysis is carried out to estimate the mechanical parameters in direct tension. Afterwards, the consistency of the processed mechanical parameters is checked by performing analytical and numerical simulations of the flexural tests, using as input the mechanical parameters calculated via inverse analysis.

Back analysis has been implemented according to the simplified 4-Point Inverse Analysis method (4P-IA) developed at Universitat Politècnica de València [17-20]. The method allows to estimate (1) the elastic modulus, (2) the first cracking stress σ_{cr}, (3) the ultimate strength f_{tu} and the corresponding strain ε_{tu} and (3) the post localization behaviour thanks to the crack opening at $f_{tu}/3$ and at nil stress. Moreover, a softening correction of the f_{tu} parameter obtained from the 4P-IA [18,26] is adopted in the case of UHPFRCC that exhibits strain-softening tensile behaviour ($f_{tu} < \sigma_{cr}$).

Once estimated the stress-strain relation in direct tension, it is used as input for the numerical/analytical simulation of the bending test. To this purpose both the Hinge Model (analytical approach described in [17-20] and based on closed-form formulations of moment-curvature relationships) and a Non-Linear FEM model described in [27] have been implemented. It is worth remarking that in the Hinge Model, the COD-strain conversion is performed with reference to the LVDT gauge length, this translating in the assumption of non-linear hinge in the multiple-cracking region [18-20].

To define the Non-Linear FEM model of the 4PBT herein used, a discrete cracking approach is considered [26-27]. The constitutive law for discrete cracking is defined by a traction-separation law. This behaviour is forced only on the mid-span section of the specimen where the macrocrack is set, as shown in Figure 3. The rest of the specimen is modelled by a smeared cracking approach based on a fixed total strain crack model. The FEM is developed by means of Diana software [28].

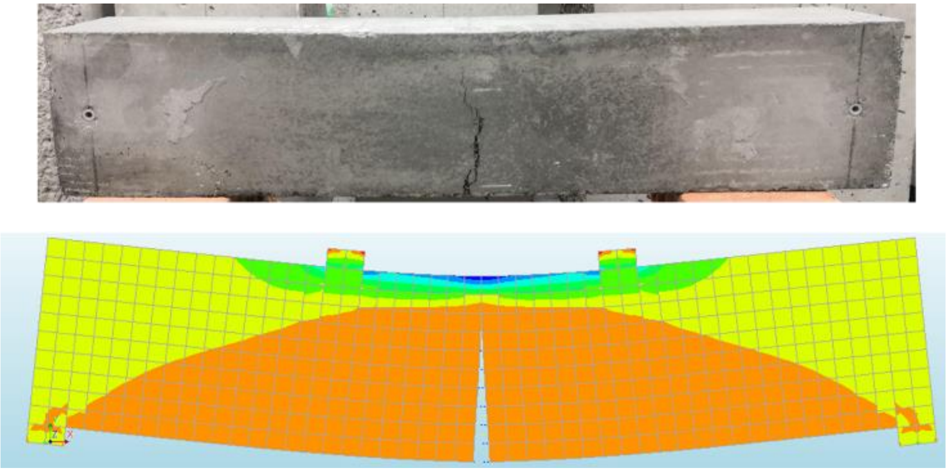


Figure 3. Non-Linear FEM model of the 4PBT.

4. RESULTS AND DISCUSSION

The experimental results on 4PBTs are reported in grey curves in Figures 4a,b,c in terms of $\sigma - \delta$ curves (where δ is the vertical mid-span displacement), the nominal stress being evaluated as:

$$\sigma = P\ L / (b\ h^2) \qquad (1)$$

where P is the total load applied, L the test span and b, h are the specimen width and thickness, respectively.

The scattering among the curves of a given mix is typical of flexural tests and it is ascribable to the possible differences in terms of fibre arrangement among the specimens and to the inherent heterogeneities of cementitious composites. The average peak stress is equal to 17, 19 and 20 MPa for mixes XA-CA, XA-CA-Amf and XA-CA-CEMIII, respectively. Mixes XA-CA and XA-CA-CEMIII are expected to yield very similar peak stress since the fibre dosage and typology is the same, and this is quite consistent with the results, the lower peak stress of XA-CA being explainable with the higher scattering of the results for this mix. On the other hand, the outcome that also mix XA-CA-Amf provides very similar peak stress to the other two mixes is rather interesting, since the fibre type is very different, consisting in amorphous metallic fibre with a very different aspect ratio.

The main difference among steel and amorphous fibre is observed in the post-localization stage, since the former seems to provide higher ductility with a less pronounced softening branch. These considerations are confirmed by the tensile parameters evaluated via 4-Point Inverse Analysis, as shown in Figure 5, where the direct σ-ε and σ-w curves are reported in grey colour. For each mix, an average curve has been also evaluated (and reported in red colour), this being instrumental for comparing effectively the three mixes (see Figure 6). It is clear as the three mixes yield an almost perfect plastic behaviour (slightly softening for mix XA-CA and slightly hardening for mixes XA-CA-Amf and XA-CA-CEMIII), with a strain-at-localization around 3-3.5‰ for the mixes with steel fibre and about 1.5 ‰ for the mix with amorphous fibre (thus corroborating what observed in the bending tests).

As a confirmation of the overall consistency of the results, the constitutive laws obtained via inverse analysis (Figure 6) have been considered as input for simulating the bending tests via both the Hinge Model and FEM analyses. In Figures 4d,e,f the comparison among experimental and analytical/numerical results is provided for one specimens per mix, showing a very good agreement.

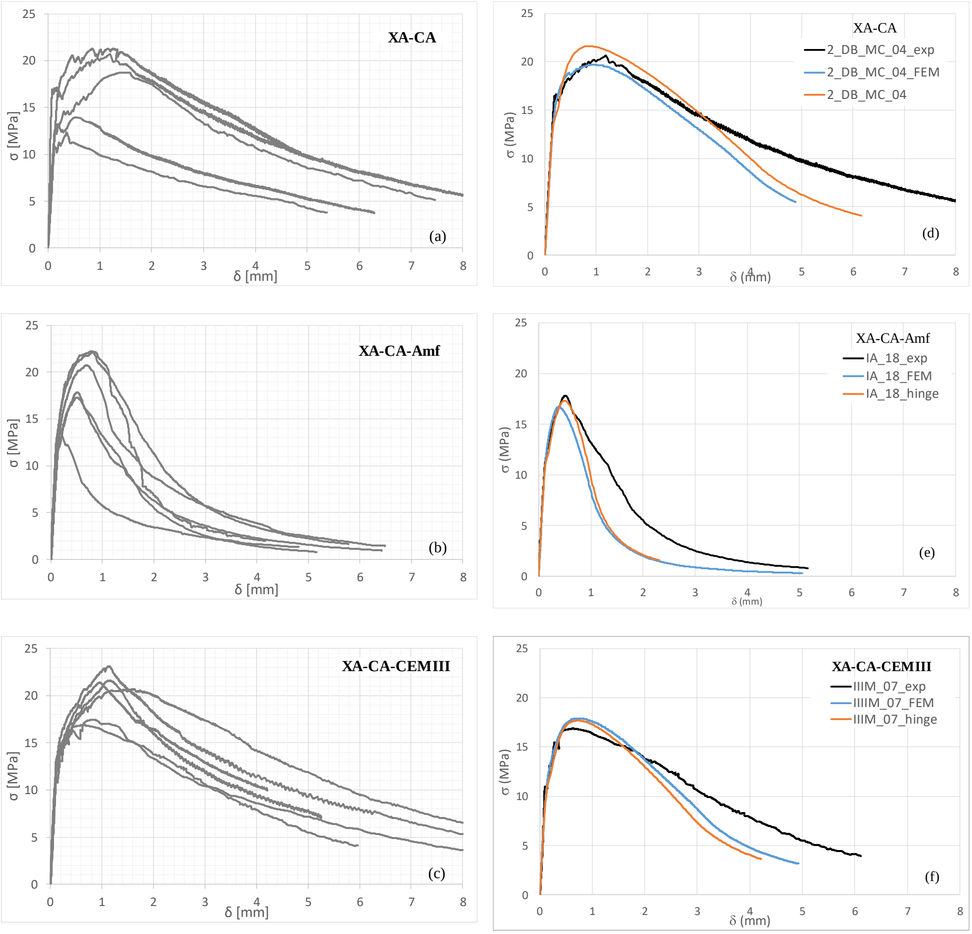


Figure 4. Plots of σ – δ curves for (a) XA-CA, (b) XA-XA-Amf and (c) XA-CA-CEMIII and (d-f) comparison among one single experimental curve and the correspondent numerical curves obtained via Hinge Model and FEM simulations.

5. CONCLUDING REMARKS

The paper describes the mechanical characterization in tension of three Ultra-High Durability Concretes (UHDC), namely Ultra High-Performance Fibre-Reinforced Cementitious Composites (UHPFRCC) conceived for specific structural applications in extremely aggressive environments.

The tensile characterization is based on an identification procedure which takes advantage of the combination of experimental tests and numerical simulations, aimed at carrying out the main mechanical parameters defining the material behaviour in direct tension. This step is fundamental for moving from the experimental scale to the structural one, thus making it possible the following structural design. The experimental investigation has been performed via 4 Point Bending Tests on 500x100x100 mm^3 small un-notched beams, while back analysis has been implemented via the 4-Point Inverse Analysis (4P-IA) method.

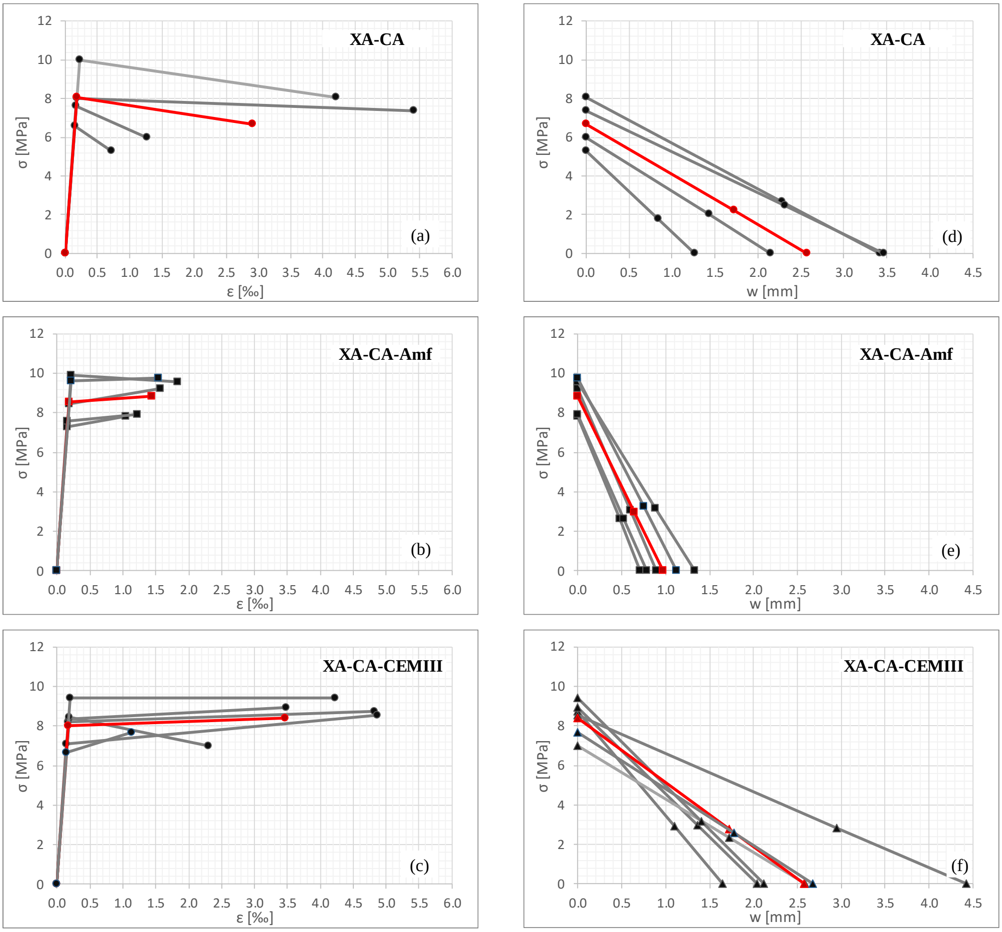


Figure 5. Plots of σ – ε and σ – δ curves in direct tension as obtained from inverse analysis for (a,d) XA-CA, (b,e) XA-CA-Amf and (c,f) XA-CA-CEMIII.

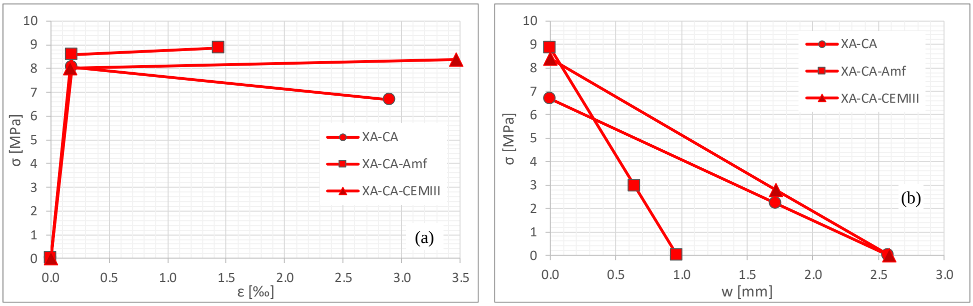


Figure 6. Comparison among the three mixes in terms of (a) σ – ε and (b) σ – δ curves in direct tension as obtained from inverse analysis.

The consistency of the constitutive laws thus evaluated has been assessed by simulating the flexural tests (via both a “traditional” Finite Element Model and the Hinge Model, this latter being an analytical approach based on bending-curvature closed-form formulations), using as input the constitutive laws evaluated by means of inverse analysis. The very good agreement among numerical and experimental curves confirms the overall reliability of the approach.

The identification procedure herein adopted, based on the cross-comparison of experimental results and numerical analysis, proved to be rather easy in implementation and effective in highlighting the overall consistency of the results. This allows to confirm an almost perfect-plastic tensile constitutive response of the investigated UHDC mixes. In particular, mix XA-CA showed a slightly softening behaviour, while mixes XA-CA-Amf and XA-CACEMIII both proved a slightly hardening response after first cracking.

On the other hand, the two mixes with steel fibre yield a higher value of strain-at-localization, this being around 3-3.5 ‰, while amorphous fibre seems to lead to a more brittle response with a value of strain-at-localization close to 1.5 ‰. In this regard, it is worth noting as 2 ‰ is an interesting threshold, this being the yield strain of ordinary steel, which could be closely achieved, or even abundantly overpassed, by all mixes. If also traditional reinforcement is used, in fact, guarantying no crack-localization of concrete at steel-yielding, allows for the optimization of reinforcement amount and durability performance.

On the other hand, the value of cracking and peak stress of the three mixes are rather similar, their average values being comprised in the range 8-9 MPa and 6-8 MPa, respectively. The promising mechanical response in tension provided by the three mixes together with the effectiveness in the identification of the main constitutive parameters via inverse analyses are the bases for the following step, namely the design of the full-scale demonstrators of the Project, these being the final testing ground of the developed procedure.

ACKNOWLEDGEMENTS

The research activity reported in this paper has been performed in the framework of the ReSHEALience project (Rethinking coastal defence and Green-energy Service infrastructures through enHancEd-durAbiLity high-performance cement-based materials) which has received funding from the European Union’s Horizon 2020 research and innovation program 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.

The authors acknowledge the cooperation of MEng. Lorenzo Papa, Stefano Passoni, Angelo Alferi, Nicola Borgioni, Andrea Cervini and Luca Famiani in performing experimental tests, in partial fulfilment of the requirements for the MEng in Civil Engineering and Building Engineering respectively.

The kind collaboration of ReSHEALience partner Penetron Italia (MArch. EnricoMaria Gastaldo Brac) in supplying the crystalline self-healing promoter is also acknowledged.

The authors also thank Mr. Marco Francini (BuzziUnicem) for supplying of cement, Mr. Michele Gadioli and Roberto Rosignoli (Azichem ltd) for supplying of steel fibres, dr Florian Bernard (Saint-Gobain Seva) for supplying of amorphous fibres and Mr. Sandro Moro (BASF Italia) for supplying the superplasticizer employed for casting the investigated UHDC mix.

REFERENCES

[1] Al-Obaidi, S., Bamonte, P., Luchini, M., Mazzantini, I. and Ferrara, L.: “Durability-based design of structures made with UHP/UHDC in extremely aggressive scenarios: application to a

geothermal water basin case study", MDPI Infrastructures, 5 (11), Nov. 2020, pp. 1-44, http://dx.doi.org/10.3390/infrastructures5110102.

[2] Serna, P.; Lo Monte, F.; Mezquida-Alcaraz, E. J.; Cuenca, E.; Mechtcherine, V.; Reichardt, M.; Peled, A.; Regev, O.; Borg, R. P.; Tretjakov, A.; Lizunov, D.; Sobolev, K.; Sideri, S.; Nelson, K.; Gastaldo Brac, E. M.; Ferrara, L., 2019, "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", Proc. of the Int. Conf. on Sustainable Materials Systems and Structures SMSS 2019, Rovinj (Croatia), March, 20 – 22, 2019, pp. 764-771.

[3] Naaman, A.E. and Reinhardt, H.W., 'Proposed classification of HPFRC composites based on their tensile response, Mats. & Structs. 39 (5) (2006) 547-555.

[4] Li, V.C. and Wu, H.C., 'Conditions for pseudo strain-hardening in fiber reinforced brittle matrix composites', Appl. Mechs. Rev., 45 (8) (1992) 390-398.

[5] Li, V.C., Stang, H. and Krenchel, H., 'Micromechanics of crack bridging in fibre-reinforced concrete', Mats. & Structs., 26 (8) (1993) 486-494.

[6] Li, V.C., 'On engineered cementitious composites. A review of the material and its applications' J. Adv. Concr. Tech., 1 (3) (2003) 215-230.

[7] T. Plagué, C. Desmettre and J. -P. Charron, 2017 "Influence of fiber type and fiber orientation on cracking and permeability of reinforced concrete under tensile loading", Cement and Concrete Research (94), 59-70.

[8] Yang, Y., Lepech, M., Yang, E., and Li, V., 'Autogenous healing of engineered cementitious composites under wet-dry cycles, Cem. Concr. Res. 39 (2009) 382-390.

[9] Zhang, Z, Qian, S. and Ma, S., 'Investigating mechanical properties and self-healing behavior of micro-cracked ECC with different volume of fly ash', Constr. Build. Mats, 52 (2014) 17-23.

[10] Ferrara, L., Ferreira, S.R., Krelani, V., Della Torre, M., Silva, F. and Toledo, R., 'Natural fibers as promoters of autogenous healing in HPFRCCs: Results from on-going Brazil-Italy cooperation'.

[11] Ferrara, L., Krelani, V. and Moretti, F., 'Autogenous healing on the recovery of mechanical performance of HPFRCCs: part 2 - correlation between healing of mechanical performance and crack sealing. Cem. Conr. Comp., 73 (2016) 299-315.

[12] Ferrara, L., Krelani, V., Moretti, F., Roig Flores, M. and Serna Ros, P., 'Effects of autogenous healing on the recovery of mechanical performance of HPFRCCs: part 1'. Cem. Concr. Comp., 83 (2017) 76-100.

[13] Snoeck, D. and De Belie, N., 'Repeated autogenous healing in strain-hardening cementitious composites by using superabsorbent polymers', ASCE J. Mats. Civ. Engrg., 28(1) (2016) 1-11.

[14] Baby F, Graybeal B, Marchand P and Toutlemonde F 2013 UHPFRC tensile behavior characterization: Inverse analysis of four-point bending test results Mater. Struct. Constr. 46 1337–54

[15] Qian S and Li V C 2007 Simplified Inverse Method for Determining the Tensile Strain Capacity of Strain Hardening Cementitious Composites J. Adv. Concr. Technol. 5 235–46

[16] Soranakom C and Mobasher B 2007 Closed-form moment-curvature expressions for homogenized fiber-reinforced concrete ACI Mater. J. 104 351–9

[17] López J Á, Serna P, Navarro-Gregori J and Camacho E 2015 An inverse analysis method based on deflection to curvature transformation to determine the tensile properties of UHPFRC Mater.

Struct. 48 3703–18.

[18] E J Mezquida-Alcaraz, J Navarro-Gregori and P Serna-Ros, 2019, “Numerical validation of a simplified inverse analysis method to characterize the tensile properties in strain-softening UHPFRC”, Fibre Concrete 2019, Materials Science and Engineering 596 (2019) 012006, doi:10.1088/1757-899X/596/1/012006.

[19] López J.Á., Serna P., Navarro-Gregori J., Camacho E., "An inverse analysis method based on deflection to curvature transformation to determine the tensile properties of UHPFRC", 2015, Materials and Structures (205) 48: 3703-3718.

[20] López J.Á., Serna P., Navarro-Gregori J., Coll H., “A simplified five-point inverse analysis method to determine the tensile properties of UHPFRC from un-notched four-point bending tests”, Composites Part B 91 (2016). 189-204.

[21] MC 2010, fib Model Code for Concrete Structures 2010, Comité Euro-International du Béton, Lausanne (Switzerland), 2012.

[22] Cuenca E., Criado M., Giménez M., Gastaldo Brac E.M., Sideri S., Tretjakov A., Alonso M.C. and Ferrara L., (2019a), “Concept of Ultra High Durability Concrete for improved durability in chemical environments: Preliminary results”, Conference on Durable Concrete for Infrastructure under Severe Conditions - Smart admixtures, self-responsiveness and nano-additions, Ghent, Belgium.

[23] Cuenca, E., Mezzena, A. and Ferrara, L.: “Synergy between crystalline admixtures and nano-constituents in enhancing autogenous healing capacity of cementitious composites under cracking and healing cycles in aggressive waters”, Construction and Building Materials, vol. 266 part B, January 2021, paper 121447, pp. 1-17, https://doi.org/10.1016/j.conbuildmat.2020.121447.

[24] Lo Monte F. and Ferrara L, “Tensile behaviour identification in Ultra-High Performance Fibre Reinforced Cementitious Composites: indirect tension tests and back analysis of flexural test results”, Materials and Structures 53 (6), (2020).

[25] Lo Monte F. and Ferrara L, “Self-healing characterization of UHPFRCC with crystalline admixture: Experimental assessment via multi-test/multi-parameter approach”, Construction and Building Materials 283, (2021).

[26] E.J. Mezquida-Alcaraz, J. Navarro-Gregori, P. Serna-Ros, Direct procedure to characterize the tensile constitutive behavior of strain-softening and strain-hardening UHPFRC, Cement and Concrete Composites 115 (2021) 103854. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2020.103854.

[27] E.J. Mezquida-Alcaraz, J. Navarro-Gregori, J. Angel Lopez, P. Serna-Ros, Validation of a non-linear hinge model for tensile behavior of UHPFRC using a Finite Element Model, Comput. Concr. 23 (2019) 11–23.

[28] DIANA (Software), User’s Manual -- Release 10.2, TNO DIANA, Netherlands. (2017). https://dianafea.com/manuals/d102/Diana.html.