Textile-reinforced concrete to realise ultra high durability concrete (UHDC) in the framework of the EU H2020 project "ReSHEALience"

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Abstract
The EU H2020 project "ReSHEALience" (rethinking coastal defence and green-energy service infrastructures through enhanced-durability high-performance cement-based materials) focuses on a holistic approach to create ultra-high durability concrete (UHDC) encompassing the concept and development of advanced materials and tailored design approaches to provide innovative structural solutions. One kind of cement-based composites to realise UHDC structures is textile-reinforced concrete (TRC), in which multiple layers of carbon multifilament yarns composed to a fabric serve as the reinforcement. TRC exhibits multiple micro-crack formation upon tensile loading with fairly small individual crack opening widths, below about 100 µm under service conditions. This characteristic in conjunction with functional admixtures is expected to reach a pronounced self-healing propensity of the cement-based matrix even under very harsh XS exposure conditions. Subsequent to durability-related laboratory experiments regarding sea water as the aggressive medium, two real-scale demonstration projects will be implemented, specifically a breakwater on the Irish west coast and the restoration of a historic water reservoir tower in Malta.
This paper presents the concept of TRC development towards a UHDC, outlines the characteristics of the two demonstrators and some preliminary laboratory results.

Keywords: Carbon multifilament; multiple micro-crack formation; self-healing; textile-reinforced concrete (TRC); ultra high durability concrete (UHDC)

1. Introduction

The EU H2020 project "ReSHEALience" (rethinking coastal defence and green-energy service infrastructures through enhanced-durability high-performance cement-based materials) advances from high-performance concretes (HPC) with superior mechanical performance to designing most durable civil engineering structures made out of cement-based composites. Starting at the material level of matrix composition and reinforcement design, general objectives include quantification and prediction of the durability of both laboratory-scale specimens and real-scale pilot structures subjected to extremely aggressive exposures. Infrastructures encompassing durability problems include, among others, coastal defence and off-shore civil works (XS, exposure to sea water) and facilities serving geothermal energy plants (XA, chemical attack). Carbon-textile reinforced concrete (TRC) is considered for two demonstration structures in XS:

breakwater pontoons on the Irish west coast and the retrofitting of a cultural-heritage water reservoir tower in the Grand Harbour, Malta. The first is exposed to cool Atlantic sea water and the latter to saline humid and hot atmosphere. The fabric layers in TRC facilitate multiple crack formation, especially upon tensile loading, with rather small individual crack openings of below about 100 µm each under service conditions. This way, permeability is limited and the self-healing capability is intrinsically high [1].
TRC is modified by innovative additions within ReSHEALience to improve both the mechanical and the self-healing performance to realise UHDC.

2. Materials and methods

Two types of TRC are analysed in ReSHEALience: one for building the breakwater pontoons, researched by Technische Universität Dresden (TUD), the other one to retrofit the outside of the drum and curved elements of a water reservoir, designed and characterised by Ben Gurion University (BGU) and the University of Malta (UoM). Intentionally, the composites designed by the university laboratories should be as close as possible to the TRCs placed in the real-scale structures later-on.
TUD uses Irish mineral constituents and the matrix layout was based on well-flowable, nearly self-compacting aspects. First, the grading curve of the mineral ingredients was optimised towards a high packing density and, hence, intrinsic workability. The final mixture design was cement CEM I 42.5 R: 414 kg/m^3, ground-granulated blast furnace slag (GGBS) 226 kg/m^3, water 192 kg/m^3 (thus, w/c 0.46 and w/b 0.30, respectively), limestone powder 200 kg/m^3, sand (0-4 mm, steady grading curve) 1298 kg/m^3, polycarboxylate-type high-range water reducing admixture (HRWRA, aqueous solution) 7 kg/m^3. The slump spread flow from the mini cone was 24 cm, V-funnel flow time 26 s, and the compressive strength reached 110 MPa at 28 days. Two layers of carbon textile are embedded in specimens for uniaxial tensile tests and, later on, permeability and self-healing experiments in the cracked state will be performed. Figure 1 shows the geometry of these 20 mm thick specimens. In principle, this experimental strategy is according to [1].
Besides, the TRC for Malta is designed by BGU aiming at a trade-off between strength, high fluidity, and a minimum number of substances used. The final recipe reads as: CEM I 52.5 1040 kg/m^3, silica fume (Elkem 920) 300 kg/m^3, water 325 kg/m^3 (thus, w/c 0.31 and w/b 0.24, respectively), HRWRA (ENT11) 26 kg/m^3. The slump flow value is 11 cm and the compressive strength 100 MPa at 28 days.
Innovative new additions are implemented to provide micro- and nano-scale reinforcement, to improve the quality of the mineral matrix by internal curing, and to enhance the self-healing capability by enabling triggered mineralisation upon ingress of water through cracks. These substances are the following:

- Alumina nanofibres (ANF): while conventional dispersions are available with 2% fibres content by weight, a new formulation with a fibre content of 10% in water is used in the project at hand. Fibre dosage is 0.25-0.75% by weight of cement (bwoc).
- Nanocellulose in form of nanofibrils (CNF) and nanocrystals (CNC): as well, newly developed suspensions with a significantly higher solids content than commonly available (i.e. higher than 7%). Their dosage should be 0.15% bwoc.
- Crystalline admixture (CA): upon initial hydration of the cement-based binder, CA is intended to remain inert. However, upon delayed contact with water, new crystals will be formed that self-heal the cracks. Recommended dosage is 0.80% bwoc [2].
- Specifically, TUD implements superabsorbent polymer (SAP, dosage 0.12% bwoc) for internal curing [3]. In parallel, BGU adds graphene nanoplatelets (GNP) to suppress water permeation and as a reinforcement at the micro-scale.

3. Results and discussion

Initially, it was demonstrated that the TRC in fact shows satisfactory multiple crack formation with rather small individual crack widths in uniaxial tensile tests (Figure 1). Figure 2 shows a typical stress-strain curve of TRC, demonstrating the fundamental functioning of BGU's composite. However, adjustments after first trials with the new additives showed that the HRWRA dosage had to be increased from 2.5 to 2.8% bwoc.

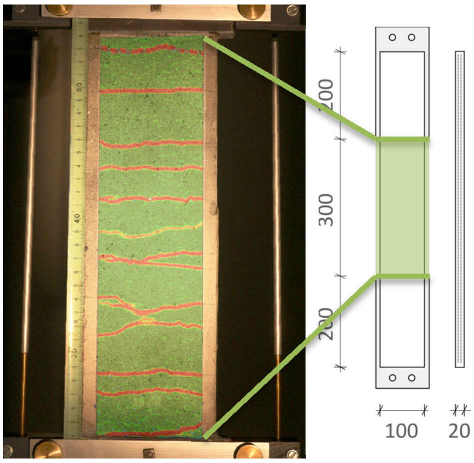

Figure 1: Photogrammetry image of cracked TRC specimen, tensile loading to 0.5% strain and its geometry, numbers in [mm], TUD

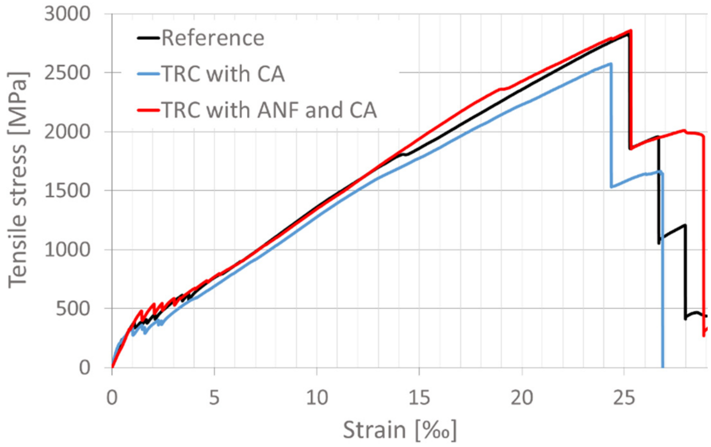

Figure 2: Stress-strain curves of BGU reference TRC and TRCs modified with the crystalline self-healing additive (CA) and alumina nanofibres (ANF), respectively

Implementation of the new admixtures resulted in the following findings so far:

- ANF neither changed workability nor flowability, whereby the compressive strength increased slightly. Preliminary TUD results on 3-point bending tests from small-batch preparation revealed increase of this mechanical property, which indicates some reinforcing effect. Further experiments will focus on potential influences of the mixing technology and mechanical performance after long-term XS exposure.
- CA neither had distinguished effects on workability nor mechanical performance. Hence, durability-related tests can initiate from this point onwards.
- CNF reduced the workability dramatically and CNC even caused a complete loss of flowability. Shrinkage was reduced to some extent.
- SAP reduced both autogenous and drying shrinkage, whereby increase of the total water content is recommended to account for the absorption by the SAP particles. Porosity derived from mercury intrusion porosimetry (MIP) showed no significant changes when implementing CNF or SAP, but both CNF and SAP can increase the capillary porosity if additional water, which is intended to act as internal curing water, is not well-adjusted to their absorption capacities.
- Preliminary results with GNP have shown a slight increase in flow, but further evaluation of other parameters relevant are due.

The TRC developed by TUD will be used in breakwater pontoon pilots. Potentially, the employed quantity of material can be reduced dramatically because empiric cover depths of steel reinforcement would be irrelevant. However, the structural entity has to comply with some minimum dead weight which is required to perform efficiently as a breakwater and not only dance on the waves (Figure 3). The TRC developed by BGU is going to be applied as external retrofitting in the drum and curved surfaces of a reservoir water tower in the Grand Harbour of Valletta (Malta), severely damaged by airborne salts and salt water (Figure 4).

Figure 3: Breakwater in service condition, houses in the background may serve as a qualitative scale

Figure 4: The steel-reinforced concrete of the water reservoir tower in the Grand Harbour region of Malta, to be retrofitted with TRC

4. Conclusion

The results shown in this paper, on the concept and preliminary characterisation results of textile reinforced cementitious composites (TRC) incorporating functionalising nano-additives in its matrix, pave the way to produce Ultra High Durable Cementitious Composites (UHDC) to be employed in structures exposed to extremely aggressive conditions. A noteworthy synergy on the mechanical behaviour of the composite has been observed between healing-stimulating crystalline admixtures and alumina nanofibres providing toughening and reinforcement at the nanoscale, which is going to be further exploited in characterising the long-term performance of the TRC under conditions representative of the structural service scenarios.

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