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Floating breakwater pontoon pilot cast with carbon textile reinforcement-based ultra high durability concrete: Materials development and testing, and implementation in the North Atlantic (Irelands west coast)

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Abstract. A floating unit with three pontoons made of epoxy-coated carbon textile reinforced, ultra-high durability concrete (ECF UHDC), mineral impregnated carbon fibre-reinforced UHDC (MCF UHDC) and, as references, steel-reinforced concretes has been designed and installed in the Northern Atlantic. While marine structures with steel reinforcement require large cover depths, which cause problems in size, cost, environmental friendliness and short service life, carbon textile reinforced concrete (TRC) cannot suffer from chloride-induced corrosion of a metal reinforcement. In the EU H2020 project "ReSHEALience" (rethinking coastal defence and green-energy service infrastructures through enhanced-durability high-performance cement-based materials), TRCs have been modified with functional admixtures from consortium partners. A mineral self-healing promoter and alumina nano-fibers have, among others, been implemented to boost high-performance concretes towards UHDCs. Resulting composite variants have been applied in a full-scale floating unit that has been launched in the harbor of Galway at the Irish West Coast in June 2020. Such a floating body is a representation of breakwaters installed to reduce wave impacts to the coast. Besides, TRC-based UHDC can be applied as strengthening and repair layer on concrete structures to enhance their service life in general.

1 Introduction

1.1 Ultra-high durability concrete (UHDC) in the EU H2020 project "ReSHEALience"

The EU H2020 "ReSHEALience" (rethinking coastal defence and green-energy service infrastructures through enhanced-durability high-performance cement-based materials, 01/2018-03/2022) project focused on enhancing the durability of high-performance cement-based composites towards ultra-high durability concrete (UHDC), both on the materials and structural levels. It had thus differed from the acquainted target in building materials research of ultimately increasing the mechanical properties of reinforced mineral-based systems. Exposure scenarios regarded were extremely aggressive environments (EAEs) XA 3 and, discussed in the present paper, XS 3 (tidal, splash and spray zones) according to EN 206-1.

Two groups of UHDC had been defined, one based on ultra-high performance fibre-reinforced concrete (UHPFRC, with dispersed short metal fibers) and the other based on textile-reinforced concrete (TRC), the latter being presented in the paper at hand [1, 2]. Pilots as real-scale demonstrator structures at TRLs 6 to 7 have been implemented as listed in Table 1.

Table 1. Countries, numbers, exposure classes (acc. to EN 206-1) and types of UHDC of the demonstrator structures in the ReSHEALience project

Country	Number of structures	Exposure class	Type of UHDC
Italy	1	XA 3	UHPFRC
Spain	2	XS 3	UHPFRC
Ireland	1	XS 3	TRC
Malta	1	XS 3	UHPFRC and TRC

The development strategy of each pilot started at combining local binder composites, aggregates, workability and processing issues of each respective partner. Reinforcement materials have been metal fibers well-established in other UHPFRCs on the one hand, and custom-made carbon textiles with polymer as well as mineral impregnation derived from previous and parallel TRC studies on the other hand. Specifically for this project consortium, new functional ingredients were introduced to enhance the durability performance in the EAEs: Nano-cellulose for micro-scale reinforcement and internal curing, alumina nano-fibers as a micro-scale reinforcement, and a crystalline admixture as a self-healing promoter [3]. Besides, experimental test procedures were adjusted to assess durability and self-

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healing performance of each material combination in a distinctly pre-cracked state that was considered characteristic for each pilot structure under its prospective mechanical loading conditions.

Numerical durability modelling, including the fuzzy-probabilistic approach to cope with only small sets of experimental results, complemented the project.

1.2 Textile reinforced concretes for the UHDC pilot structure exposed to Atlantic seawater

A fundamental motivation to study TRC-based UHDC is the mere absence of any metal reinforcement with the consequence that chloride-induced metal corrosion of a reinforcement cannot take place. TRC features multiple crack formation with tiny individual crack widths (as compared to conventionally reinforced concrete), and it is hence prone to enhanced self-healing [4]. The following aspects complemented the use of TR-UHDC for the pilot structure in the EAE XS 3 scenario:

- Reduce the section size requirements in the marine environment by cutting down cover depths of concrete atop the reinforcement necessary for corrosion inhibition,
- Explore alternatives to stainless steel reinforcement which is 50 times more expensive than commonly used steel qualities as a reinforcement,
- Replacement of galvanized steel with carbon textile reinforcement, whereby both epoxy-coated (ECF) and mineral impregnated (MCF) yarns and fabrics are investigated,
- Cut down transport costs for the precaster because pronouncedly reduced section sizes require considerably less concrete volume for equivalent mechanical and durability performance.

The pilot was to be implemented at the Irish West Coast in the harbor of Galway. On the long term, such breakwater structure should be installed off the coast line to act purposefully, e.g. in midst the mouth of a major river to the sea or off shore in front of a marina. However, for the ease of access, monitoring and individual inspection, the pilot within this project was decided to be located in a harbor. Naturally, the exposure to the sea water is the same as off shore, but the wave agitations are presumably less intense. Distinct wave agitation can, however, occur from time to time in the course of heavy storms and floodings of the entire port area. Since the launch of the structure in June 2020, none of such events had occurred until issuing this paper in early 2023.

2 Experimental

2.1 UHDC compositions and pontoon design

The primary scope of the present unit has been to investigate as many material and durability performance parameters as possible within a single structure. The overall structure consists of three pontoons linked by a slab, whereby each of the pontoons has an individual cement-based material design, and an additional block of further variations of concretes (Fig. 1, Table 2).

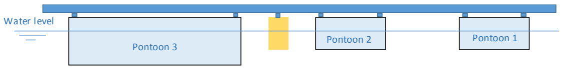

Fig. 1. Scheme of the floating unit, the additional block colored yellow in the middle beneath the connecting slab.

Table 2. Pontoon dimensions and compositions.

Pontoon	**Dimension (cm x cm x cm)**	**Reinforce-ment**	**Concrete mixture**
1	122 x 300 x 57	MCF	UHDC B'
2	122 x 300 x 57	ECF	UHDC B'
3	300 x 300 x 86	Galv. steel, ord. steel	UHDC A'
Extra prism	24 x 25 x 50	Ord. steel, ECF	Ord. concr., mixture B

TRC compositions of TU Dresden with respect to typical binder contents and fundamental particle grading recommendations were modified towards UHDCs using raw materials from the project partner Banagher Precast, available in industrial-scale quantities: Cement (CEM I 42.5 R, Irish Cement Ltd., Ireland), ground granulated blast furnace slag ("GGBS", Irish Cement Ltd., Ireland), limestone powder (Omya, United Kingdom), sand 0-2 mm and sand 0-4 mm (proprietary gravel source by Banagher Precast close to the factory, screened and washed, each with fairly steady grading) and high-range water-reducing admixture ("SP", MasterMatrix 233, BASF, Germany). The characteristic admixtures of the ReSHEALience project to implement enhanced durability performance were the crystalline self-healing promoter "CA" (PENETRON ADMIX®, Penetron, Italy) and reinforcement on the nano-scale in form of an aqueous alumina nano-fibers dispersion ("ANF" by ANF Development, Latvia and United Kingdom). A steady grading among all major ingredients was aimed at in order to obtain self-levelling properties from this perspective as far as possible, and consequently keep the SP dosage at a low level. Fig. 2 shows the result for mixture composition UHDC A'. Table 3 indicates the distinct concrete compositions. The sands were used as-delivered; their gradings were not modified. Measurements according to EN 12620 have revealed that the gradings are steady and the granulation coefficient of the sand 0-2 is 2.09 and that of sand 0-4 is 2.90, respectively. However, for academic analytics, their size distributions were analyzed in the fractions 0-1 and 1-2 and, where applicable, 2-4 mm (cf. Fig. 2). ANF contents are provided by suspension used, whereby the dosage of 0.25 % by mass of cement takes into account the active agent within the aqueous suspension.

The reference UHDC was not implemented in the pilot structure, but used for the sake of assessing the efficiency of CA and ANF in durability performance with laboratory experiments only.

Preliminary laboratory tests had revealed that neither the third typical UHDC admixture in the ReSHEALience project, nano-cellulose, nor a superabsorbent polymer (SAP), both being internal curing agents, would further improve the durability performance. They were thus not implemented in the pilot structure.

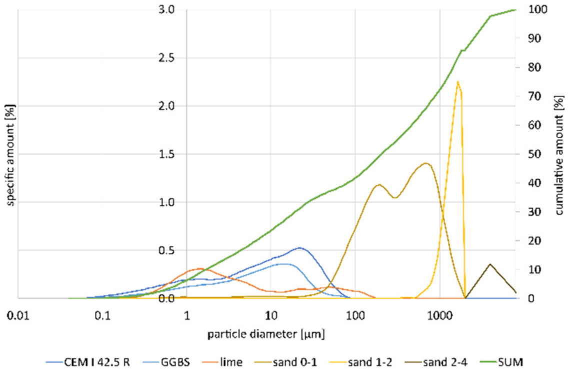

Fig. 2. Composed particle size distribution of the basic ingredients towards UHDC A'.

Table 3. Concrete compositions, number values kg/m^3; CA dosage being 0.80 and ANF 0.25 % active agent by mass of cement, respectively.

Material	UHDC ref.	UHDC A'	UHDC B'	Mixt. B	Ord. concr.
Cement	414.5	411.7	475.0	475.0	275.0
GGBS	226.1	226.4	261.2	261.2	151.2
Lime	200.9	200.0	230.8	230.8	600.0
Sand 0-2	0	0	1090	1090	0
Sand 0-4	1298	1297	0	0	1090
SP	7.5	7.5	14.0	14.0	7.0
CA	0	3.3	3.8	3.8	0
ANF	0	8.2	0	11.9	0
Water	192.2	219.5	271.6	208.0	191.8
w/binder ratio	0.30	0.34	0.37	0.30	0.30

As textile reinforcement, commercially available ECF (Grid Q85/85-CCE-21, Solidian, Germany, Fig. 3 left) and TU Dresden's custom-made mineral impregnated carbon multifilaments [5, 6] (Fig. 3 right) were used.

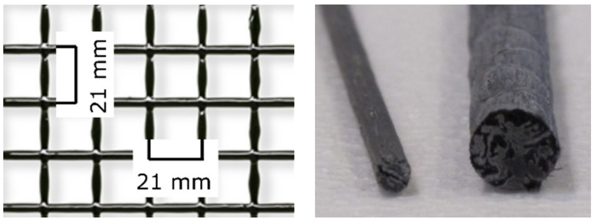

Fig. 3. ECF carbon textile reinforcement (left) and exemplary MCF multifilaments (right, diameters 2 and 4 mm).

2.2 Performance tests

Besides mechanical characterisation of non-reinforced specimens as well as reinforced composite slabs (not included here), durability performance indicators were assessed on behalf of laboratory-scale mineral-only, un-cracked specimens. Indirect indicator types assessed were mercury intrusion porosimetry (according to DIN ISO 15901-1) and microstructure imaging using an environmental scanning electron microscope (Quanta 250, FEI, The Netherlands; low-vacuum mode without sputter coating) with energy dispersive X-ray analysis (Quantax 400, Bruker, Germany). Direct indicators relevant in the XS exposure scenario were capillary suction and chloride transport. Time-resolved gravimetry to assess absorption kinetics by capillary suction was conducted according to DIN EN ISO 15148. Cylindrical specimens (diameter 150 mm, height 150 mm) were cast and stored under water for 28 days. 20 mm slices were then cut each from bottom and top and discarded. The remaining body was sliced in 30 mm thick plates, dried until mass constancy and used for the capillary intake of liquid through the bottom face. The water absorption coefficient was calculated from the mass increase after 24 hours.

Assessment of the chloride migration coefficient was comparable to NT-BUILD 492. The procedure was in accordance to the "Code of practice: Chloride penetration resistance" issued by the German Federal Waterways Engineering and Research Institute) in principle. However, instead of cylindrical specimens with diameter 100 mm and height 50 mm, equivalent slices to the capillary water suction were used for practical reasons. Such discrepancy was acceptable since the depth of chloride ingress did not exceed 15 mm in any single specimen. Next, the prescribed testing age (56 days) was pronouncedly exceeded for schedule reasons in the laboratory process. The durations of chloride migration are indicated in the results chart. The border between chloride-loaded and unaffected concrete parts was quantified from digital light microscopy images (VHX 6000, Keyence, Germany) at cut halves (dry sawing, cooling by a stream of pressurized air).

The self-healing efficiency of mechanically pre-cracked reinforced specimens was a crucial part of the durability assessment. In this part of the study, UHDCs with ANF and both the single (cf. Table 3) and double CA dosage, as well as additionally SAP-containing mixtures were regarded. ECF was implemented as the reinforcement. Uniaxial tensile loading created a multiple crack pattern with rather tiny individual crack openings, which is characteristic for TRC. Slabs (thickness 20 mm, width 700 mm, length 70 mm, free length of tensile loading 300 mm between the clamps) were loaded to elongation 0.55 %. From typical positions, each of which featured some of the cracks, were specimens extracted (lateral dimensions of 100 mm times 100 mm). Un-cracked reference plates were taken from the clamped parts. The extracted samples were cured in tap water and sodium chloride solution (3 wt-% NaCl in tap water), respectively, whereby water immersion was continuous and that in NaCl solution both continuous and in wet/dry cycles. Crack widths were measured time-resolved until at least 107 days. Evolvement, i.e. decrease, of these crack widths in time served as the major durability and self-healing indicator. The specimens were taken out of the curing bath short before each imaging, carefully dried at their surfaces prior to image recording, and quickly re-immersed in the curing solutions afterwards to continue the self-healing. Per each crack, five specific points along its path on the plan view were selected and the distances of the crack edges were measured there. The crack widths were classified in four groups: Up to 50 µm, 50 to 100 µm, 100 to 150 µm, and wider than 150 µm. Most cracks were below 150 µm. It was possible that no crack populated one of these specific intervals, and up to six cracks were present in each size class. The self-healing extent over time was calculated both in absolute numbers of width reduction and the relative decrease in width referenced to the original value at the respective location. Strictly speaking, the self-sealing extent was recorded.

2.3 Pontoon implementation

For the pilot structure, pontoons 2 and 3 were produced in Banagher according to common protocols of the company. ECF fabric layers and custom-knitted steel bars, respectively, were implemented as reinforcement around a core of expanded polystyrene (EPS). On the other hand, the EPS core for pontoon 1 was surrounded by MCF reinforcement at TU Dresden (Fig. 4) and shipped to Banagher for further processing, i.e. equipping it with sensors and casting the concrete. The extra prism for the floating unit was prepared at TU Dresden, using a Zyklos zk30he mixer (Pemat Mischtechnik GmbH, Germany) for Mixture B according to good laboratory practice. Further modified ordinary concretes were realized for parts of this extra prism, in conjunction with the latter composition. However, these are beyond the scope of the report at hand and are thus not included here.

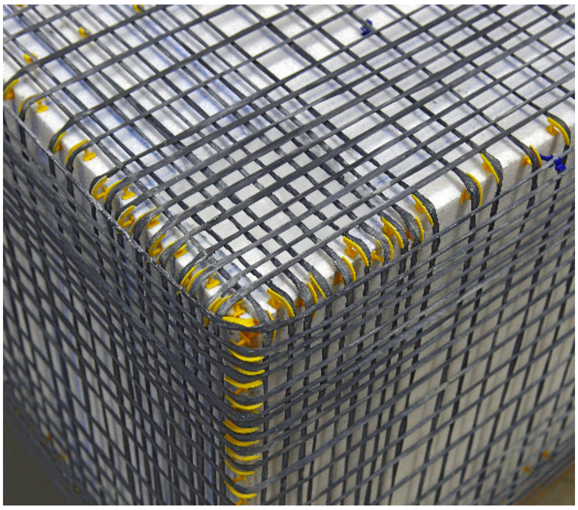

Fig. 4. Prepared inner body of the floater surrounded by custom-made MCF reinforcement cage.

After the assembly the pontoon was transferred from its production site at Banagher's to the port in Galway and installed there in June 2020. Ever since, it has been floating there and it continuously monitored (details of monitoring results not to be presented in the paper at hand).

3 Results and Discussion

This pilot embedded in the ReSHEALience project is a floating unit which is a representation of a breakwater installed to calm down wave movements in coastal areas. It is a full-scale demonstrator structure for such units made of precast elements. For in-fact application, however, distinct geometries may have to be adjusted.

3.1 UHDC properties and durability performance

Table 4 summarizes the porosity of the UHDCs. From a size distribution point of view, most of the capillary pores had diameters below 0.1 µm, and only very few were in the range of larger than 1 µm. This fine pore structure, in conjunction with the generally fairly low overall porosity, is advantageous for high durability.

Table 4. Porosity of UHDCs as obtained from MIP.

Porosity [vol-%]	Reference UHDC	UHDC with CA	UHDC with ANF
7 days	9.0	9.8	10.3
28 days	7.3	7.5	7.9

An exemplary electron microscopy image (Fig. 5) of the hardened UHDC matrix with CA indicates rather dense microstructure. The main aggregate being calcareous sand, which is typical for its Irish source, extensive calcium carbonate formations have developed all over the matrix volume. Besides, tiny but minor cracks are observed, which most likely stem from shrinkage processes at the earlier stages of solidification and densification.

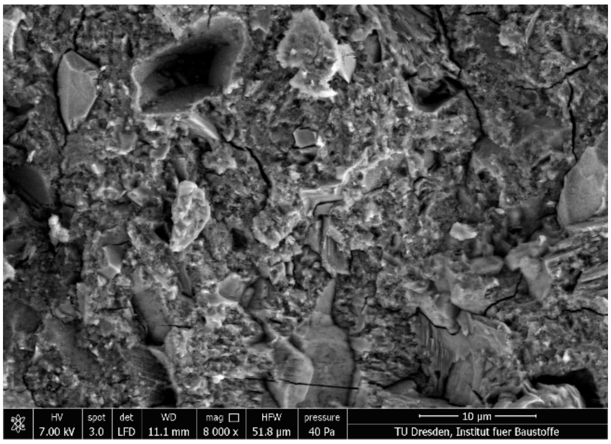

Fig. 5. Exemplary ESEM image of UHDC matrix with CA.

Shrinkage tests of UHDC mixtures containing an admixture for internal curing (not included here), i.e. nano-cellulose or SAP, respectively, had revealed that shrinkage could indeed be reduced by them. However, the overall view of the durability performance was roughly a zero-effect with these functional ingredients, including porosity evolvement and capillary suction intensity. None of these admixtures were thus inserted in the final mixtures to produce the pontoons for the sake of saving material and financial efforts.

Table 5 gives the linear water absorption coefficients as calculated from the mass increase during 24 hours of capillary suction.

Table 5. Water absorption coefficients of un-cracked UHDC.

$g/(m^2\sqrt{min})$	Reference UHDC	UHDC with CA	UHDC with ANF
$W_{w,24h}$	3.5 ± 0.2	4.2 ± 0.7	3.5 ± 0.1

The capillary suction activities are very close to each other. A potential reason for the marginally higher value in UHDC with the CA might be a consequence of the slightly higher water-to-binder ratio (cf. Table 3), which could be in line with results of the chloride migration coefficient (cf. Table 6). Interestingly, that had no detectible effect on capillary porosity (cf. table 4). But since all UHDC values for the un-cracked materials are in fact in the very same order of magnitude, no further attention was paid to these variances. The respective coefficients of UHDCs with an internal curing agent were slightly bigger but still in the same order of magnitude: With nano-cellulose 4.9 ± 0.1, with SAP 5.0 ± 0.1 (unit g/($m^2\sqrt{min}$)).

On behalf of Fig. 6 the quantification of the depth of chloride ingress is illustrated. At a magnification of 200 two images were taken of each specimen, each covering about 40 mm of width left and right from the cutting diameter face. Using the scale tool the position of the chloride border was measured every 5 mm. This way, 16 to 18 single points were obtained per sample. The chloride migration coefficients were calculated from their average according to the code.

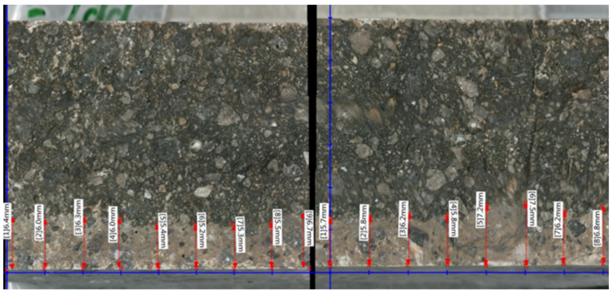

Fig. 6. Exemplary microscopy images with inlay of chloride penetration depths of UHDC with ANF; the red arrows are equidistantly 5 mm apart from each other.

Table 6 shows the results of the chloride migration coefficients. The testing ages are indicated because they were much longer than the recommended durations. On the whole and large, all chloride migration coefficients are in the same order of magnitude.

Table 6. Chloride migration coefficients of UHDCs.

	Reference UHDC	**UHDC with CA**	**UHDC with ANF**
D_{cl} [$*10^{-12}$ m^2/s]	1.18 ± 0.04	1.61 ± 0.01	1.44 ± 0.15
Test age [d]	88	90	84

The ReSHEALience consortium had aimed at a chloride migration coefficient below $1.0 \cdot 10^{-12}$ m^2/s. Indeed, this target was failed. However, that pre-specified number had been set on the basis of utmost lowering the chloride ingress ability to avoid or delay the onset of metal reinforcement corrosion to a maximum feasible extent. Since the pilot structure at hand lacks metallic reinforcement that could be corroded by chloride enrichment in the cement-based matrix, such target had turned out to be simply meaningless.

To avoid corrosion of metal reinforcement in principle, carbon multifilaments and nonwoven fabrics were used as the reinforcement. On the one hand, epoxy-based polymer-impregnated carbon textile was implemented. On the other hand, complementing parallel research at TU Dresden, carbon multifilaments impregnated by an inorganic particle suspension instead of a polymer were generated. This type of impregnation features enhanced bond properties among the numerous carbon filaments and the concrete matrix. The impregnation suspension penetrates throughout the entire bundle of fibers and creates carbon/mineral bond around each single filament at first stage and the outer mineral circumference bonds intensely with the bulk matrix at second stage. This way, a polymer/mineral interface at the outer surroundings of the multifilament bundle is avoided, which is beneficial for the mechanical performance of the composite [5, 6]. As well, potential softening of fundamentally thermoplastic polymer at elevated operating temperatures is avoided.

The self-healing (self-sealing) progress of the UHDCs is illustrated in Fig. 7 exemplarily for one class of initial crack widths (50 to 100 µm).

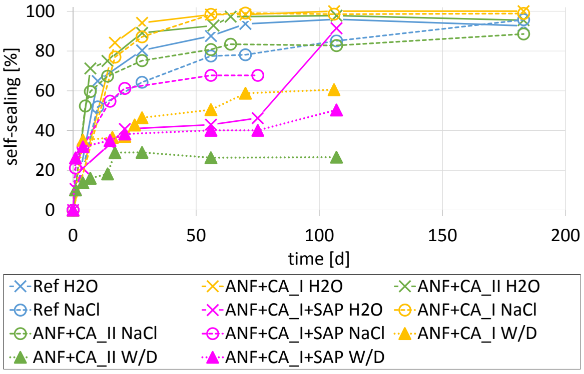

Fig. 7. Exemplary relative crack widths over time of the pre-cracked UHDCs, initial crack widths between 50 and 100 µm, two dosages of CA with respect to Table 2 being CA_I given there and CA_II double amount; self-sealing 100 % means complete crack closure; curing regimes are tap water (H2O), 3 % NaCl solution continuous (NaCl) and as wet/dry cycles (W/D).

Overall, it was found that all cracks clearly reduced their width over time, even those wider than 150 µm. In more detail, cracks between 0 and 50 µm had reached their final values (which lay between 100 % for most UHDCs and 60 % for CA-ANF-SAP in NaCl wet/dry) from 28 days. In all of the wider classes of openings, the majority of cracks had reached their final values after 50 or more days at the latest, whereby many of them remained constant after 14 to 28 days already. Related to unmodified TRC, the TR-UHDCs with CA and ANF in their respectively recommended dosages increased the self-healing extent by 5 to 15 % with exposure to water and NaCl solution permanently, whereby wet/dry cycles caused a slight worsening. Such improvement rates of 5 to 15 % may read quite little, but it should be considered that the plain TRC does already feature prominent self-healing due the characteristic multiple crack pattern. Doubling the dosage of CA did not yield improvement. Interestingly, SAP could not enhance the self-healing extent. Obviously, the type of SAP selected (sorption kinetics, grading) and its dosage was inefficient in these terms. This finding is in line with data from the literature that SAPs beneficial for internal curing are not necessarily performing well in terms of self-healing of concrete [7].

3.2 Pontoon implementation

Finally, Figs. 8 and 9 show views of the pilot structure. The entire body is 9 m in length and 3 m in width, composed of a galvanized steel frame with GRC decking and three pontoons. Traditionally, all pontoons have the same concrete design and therefore the same size. Due to the differences in wall thickness between the traditional and the newly designed TRC-based pontoons, sizes and weights of the pontoons were selected uneven to keep the buoyance well-balanced, see also Fig. 1. The additional body was mounted in the central region.

Fig. 8. Pre-assembled pontoon, in front the TR-UHDC floating units freshly mounted beneath the connecting frame.

Fig. 9. TR-UHDC floating unit under the connecting frame of the pontoon, without any sign of degradation after 15 months of immersion in sea water in the Galway port area.

4 Summary, Conclusions, Outlook

This pilot pontoon has successfully proven production and implementation of TR-UHDC (TRL 6) in exposure class XS 3. It represents a ground-breaking modification of concrete products that fundamentally overcomes the severe corrosion mechanism of metal degradation in the reinforcement. The carbon multifilaments and their mineral or polymer-based impregnations are chemically inert against chloride ions and chloride-induced pH changes inside the concrete matrix. While fundamental issues such as mixture design and textile reinforcement manufacture on the laboratory scale have been clarified, procedural steps towards mass-production in an industrial scale must be addressed in upcoming work. Polymer impregnated textiles (like the ECF used in the project at hand) are available as trade products for the use as reinforcement to cement-based composites already. However, large-scale generation of the MCF still needs process development, based on custom-made laboratory-scale systems operated up to date. As well, reinforcement assembly from MCF has not yet reached a stage very suitable for mass-production.

The self-healing ability of TRC is in general better as compared to conventionally (i.e. steel) reinforced concrete. Still, the combination of (alumina) nano-fibers and a crystalline self-healing promoting agent contained in the concrete mixture further improves this performance, even in the severe XS 3 exposure scenario. Hence, from an application point of view, TRC-based UHDC can be beneficial for far reaching benefits in all marine work and inland infrastructure which is contacted by chloride solutions, e.g. roads and bridges exposed to de-icing salts.

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