SMART reinforced and geopolymer concrete with enhanced durability: MAREWIND solution, a case study.

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ABSTRACT: In the frame of MAREWIND project (founded by the European Union's Horizon 2020 research and innovation program under Grant Agreement N° 952960), an innovative and green concrete formulation based on Alkali – Activated Materials (AAM) and a Structural Health Monitoring (SHM) system based on Fibre Optic (FO) sensors integrated in FRP rebars (defined for this reason SMART Rebars) have been developed for the application in Ground Based Structures (GBS) of offshore wind farms.

Combined use of AAMs with SMART FRP rebars should thus provide an innovative green solution avoiding problems of chloride attack in steel reinforcing bars and therefore increasing reliability and durability.

The results of validation tests and experimental program related to mechanical tests (i.e. compression tests, indirect tensile test and flexural strength tests, etc.) that was carried out to assess the performance of the presented innovative solution are presented in the work.

1. INTRODUCTION

Traditional construction materials generally undergo a number of durability threats during the service life which are even magnified in harsh environment as the marine one. Mineral-based concrete made of eco-efficient AAMs (Alkali Activated Materials) are used in MAREWIND project (founded by the European Union's Horizon 2020 research and innovation program under Grant Agreement N° 952960) to overcome durability problems of traditional concrete when exposed to chloride, organic acids and sulphate attacks. Additionally, non-metallic reinforcements based on FRP (Fiber Reinforced Polymers) are used to overcome any potential durability problems related to steel corrosion. Furthermore, such reinforcement are sensorized with embedded Fibre Optic sensors to realize a Structural Health Monitoring (SHM) system able to provide real-time feedback of the structural beaviour of components, thus becoming SMART FRP rebars.

Alkali-activated materials (AAMs) are alternative green materials that have a high potential as alternative binder as compared to ordinary Portland cement (OPC), because of their high performance (high early strength, good resistance against acid and sulphate attack, etc.) beside lower CO2 emissions.

However, these materials present different problems, such as quick setting time, poor workability and high shrinkage. These problems are related to the type of slag that is used and, therefore, vary according to their chemical composition; The mixtures developed in the project have been optimized to reduce these effects. During the experimental activities these problems were mitigated by optimizing the powder - activator ratios and the type of aggregates.

SMART FRP rebars as reinforcement in concrete provide to the structure the advantages of FRP rebars (lightness, high mechanical strength and no corrosion) and the ability to monitor the strain evolution of the structure, from the casting throughout its entire service life, allowing the reduction of maintenance costs and time.

Fibre Optic (FO) cables are made of different concentric cables. The first two cables (core and cladding) are, generally, glass cables of 9 nm and 125 nm diameters, respectively. They are the wave guide that confines and transmits the light inside the FO and are known

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as bare FO. Because of the high brittleness of these cables, bare FO are normally coated with further cables, known as protective coatings, able to increase the strength of the FO. When used as strain sensors, the FO cable must transfer the applied strain without any slippage between the different layers of coatings, thus bare fibres would appear to be most suitable FO to be used. However, bare cables are brittle and unsuitable in a harsh environment. Therefore, strain sensing cables with an acrylate coating (final diameter 250 µm) to serve as a protection layer have been used.

2. DEVELOPMENT OF NEW CEMENT FREE SMART REINFORCED CONCRETE

2.1 Alkali-activated materials (AAMs) characteristics

One of the objectives of the MAREWIND project, concerns the development of a cementless concrete based on alkaline activators with physical characteristics, resistance and durability comparable to ordinary Portland concrete (OPC). This article provides information on the fresh and hardened state characterization of the geoconglomerate developed, while the durability tests (NT Build NT-492 and AASHTO T358: chloride intrusion, EN 12390-8: water penetration resistance and ASTM C666: material freeze/thaw resistance) are still in progress. Furthermore, since activated alkaline materials have a very viscous behavior and generally have very fast setting times (fast short-term strength development), they are difficult materials to mix and use. For this reason, another objective of the experimental program is also to verify that the viscosity of the material and the rapid setting time give not negatively affect the survival of the fiber optic sensors embedded in the concrete during the curing time. The development of geopolymer concrete involved the design of different mixtures for which components were mixed in different proportions and couplings in order to obtain a conglomerate with characteristics in the fresh and the hardened state comparable to the ordinary Portland concrete (OPC) generally used for the offshore wind industry. The experimental program involved the use of glass powders and blast furnace slags activated with water, sodium silicate and sodium hydroxide for the development of the geopolymer binder and three different types of sands for the development of the mortars. Once the goodness of the binder and mortar was verified, the coarse aggregates were used to create and optimize the final geo-conglomerate. The fine and coarse natural aggregates (NA), fine recycled aggregates (RA) and fine natural magnetite (NM) was characterized according to UNI EN 1097-6, the results are showed in Table 1.

Table 1: Material Density and Absorbition

Material	**Size**	**Density**	**Absorbition**
	[mm]	**[kg/m3]**	**[w %]**
GGBS	filler	2780	/
GLASS	filler	1400	0
NA	0-4	2700	4.97
NA	4-9	2600	1.00
RA	0-4	2300	9.86
RA	4-9	2400	5.72
NM	0-2	5100	0.30

Chemical compositional data of GGBS are reported in the technical data sheets that shows the following components CaO (43.4%), SiO2 (36.4%) and Al2O3 (12.1%). Regarding the activators, according to the producer, the alkaline solution (Ingessil) has sodium silicate percentage 41.7-45.0 % and SiO_2/Na_2O mass ratio in the range 1.60-1.70.

Figure 1: Aggregate characterization

2.2 Concrete mixture design

Due to its viscosity and rapid setting time, before designing the geoconglomerate, to avoid excessive consumption of materials and safeguarding equipment, six different binders were developed to evaluate their rheological behavior and compressive strength, therefore, excluding the contribution of the aggregates. To optimize the binder, blast furnace slag and glass powder were mixed in proportions of 70% - 30% and 80% - 20% respectively with water, sodium silicate and sodium hydroxide. The binders were designed with water/binder ratios (w/b) ranging from 0.35 to 0.50. After fifteen minutes of mixing, they were subjected to the workability test according to the standard UNI EN 1015-3 (Test methods for masonry mortars - Part 3: Determination of the consistency of fresh mortar), density test, compressive strength (UNI EN 12390-3). After choosing the binder with the best performance in terms of workability and compressive strength, the same tests were performed on the mortars using normalized sand, natural sand, recycled sand and natural magnetite. The recycled sand, from the demolition of prefabricated elements, was used to increase the sustainability of the mix design, while natural magnetite, from LKAB company, was used to increase density and reduce heat of hydration. In fact, during the days of curing, the binders showed some shrinkage cracks due to the high heat of hydration and the absence of aggregates. Considering the fresh and hardened characteristics of the binders and mortars, subsequent activities focused on the design of the geoconglomerate and its characterization in the fresh (density, slump test and air content) and hardened state (density, compressive strength, and indirect tensile test).

2.3 SMART FRP rebar realization

As far as it concerns the SMART FRP rebar realization, among the others, the near surface bonded technique, consisting in bonding the FO sensors with the rebar (both on the surface or in a groove realized on the surface of the rebar), was chosen. In particular it was chosen to embed the FO in a precut groove on the rebar (

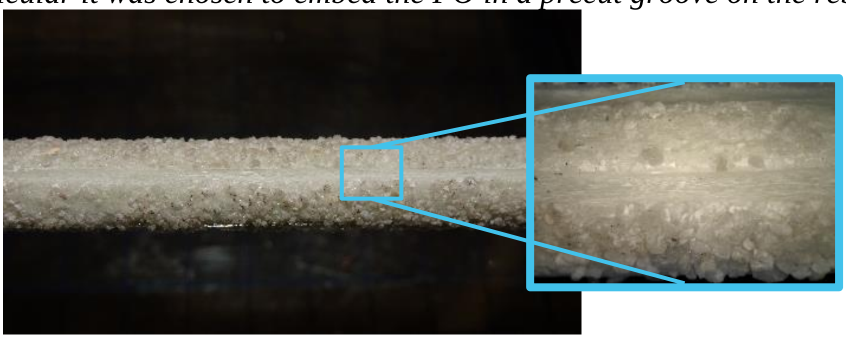

Figure 2), because it was shown that merely attaching the fiber to the rebar or even gluing it to the rebar may not ensure the same deformation of both the fiber and rebar (Sieńko, 2018; Marc Quiertant, 2012). Moreover, a mechanical cut helps to ensure the groove to be straight and with even depth, which is essential for preventing premature failure of the fiber.

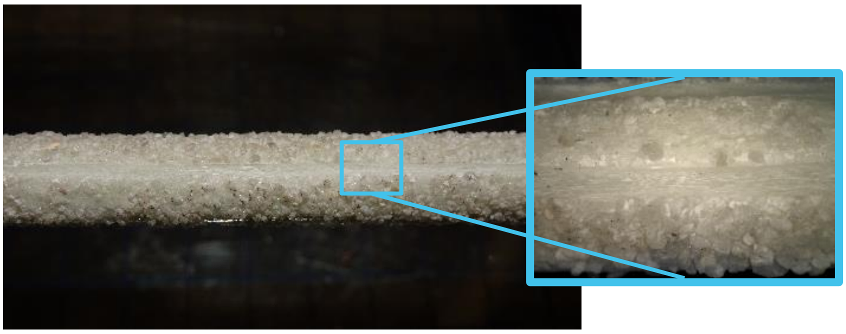

Figure 2: Groove on an improved superficial adherence GFRP rebar; in the light - blue inset an optical microscope image of the groove.

The technique was proved on rebars with different typologies of superficial finishes (smooth, enhanced adherence, veining) and it resulted adequate for all. Thus a 250 µm diameter acrylate coated FO was inserted in the groove and fixed punctually with 3M Scotch-Weld™ epoxy adhesive DP490.

3. EXPERIMENTAL CHARACTERIZATION AND MECHANICAL TEST PROGRAM

3.1 AAM concrete characterization

The results of the characterization tests conducted on the binders, mortars and geoconglomerate developed during the experimental campaign are shown below. For each of these elements a preliminary characterization of fresh and hardened states was realized to select the best formulation. Thus, once defined the best AAM formulation, mechanical characterization of the concrete was realized by means of compressive and indirect tensile strengths tests.

3.1.1 Binders characterization

As shown in table 2, the most suitable binders to be used for making mortars and concretes seem to be those with a w/b ratio of 0.35. Furthermore, lowering the percentage of glass from 30% to 20% further improves workability.

Table 2: Results of fresh state binder tests

ID	**w/b**	**Slag/Glass**	**Workability**	
		%	**Consistency**	**mm**
Binder 1	0.50	70/30	Fluid	>300
Binder 2	0.40	70/30	Fluid	300
Binder 3	0.35	70/30	Workable	180
Binder 4	0.50	80/20	Fluid	>300
Binder 5	0.40	80/20	Fluid	300
Binder 6	0.35	80/20	Workable	240

The above reported results were also found in the hardened state characterization; in fact, as shown in Table 3, all the specimens showed good compressive strengths from the first days of curing.

3.1.2 Mortars characterization

As for the binders, the mortars were also characterized in the fresh and hardened state. In this case, having chosen the best binder (binder 6 with w/b = 0.35), it was mixed with the previously characterized sands. The results in Table 4 show, as happened for binders, workability and consistency acceptable rheological behaviour.

Table 3: Results of hardened state binder tests

ID	Compressive strength			Density
	MPa			Kg/mc
	2 days	7 days	14 days	14 days
Binder 1	27.2	49.2	54.9	1631.9
Binder 2	30.2	44.7	45.6	1640.6
Binder 3	42.8	52.5	56.3	1718.8
Binder 4	53.7	58.4	52.5	1691.0
Binder 5	52.2	59.9	56.5	1769.1
Binder 6	84.5	74.7	67.4	1850.0

Table 4: Results of fresh state mortar tests

ID	w/b	Aggregates	Slag/ Glass	Workability	
		%	%	Consistency	mm
Mortar 1	0.35	100 NS	80/20	Dry	240
Mortar 2		100 NM		Fluid	220
Mortar 3		50 RA/50 NM		Workable	220
Mortar 4		50 NA/50 NM		Workable	220

Table 5 shows the results of the compression and density tests. It was found that the interaction between the cementless binder bonded perfectly with the different types of sand, providing very high compressive strengths close to 85 Mpa.

Table 5: Results of hardened state mortars tests

ID	Compressive strength				Density
	MPa				Kg/m^3
	3 days	7 days	14 days	28 days	
Mortar 1	/	56.1	55.1	58.3	2242.2
Mortar 2	49.2	58.8	72.6	78.6	2503.9
Mortar 3	59.8	66.3	69.3	83.7	2296.9
Mortar 4	54.3	61.2	67.8	74.5	2257.8

3.1.3 Concrete characterization

In order to achieve the desirable workability and to be able to make comparisons five mixtures were prepared and tested. The same binder developed in the first phase of the experimental program and used for the realization of the mortars was subsequently used for the design and development of the geopolymer concrete. The different mix designs have been designed and tested, the best of which has been optimized and subjected to mechanical and durability tests. As mentioned above, the durability tests, are still ongoing and, therefore, the results are not included in this paper. To facilitate the flow of concrete between the reinforcing bars of the foundation prototype of the offshore wind turbine, aggregates with a maximum diameter of 9 millimeters were chosen. The different percentages and types of aggregates used in the mix designs are shown in table 6.

Table 6: Percentage of aggregates used in the mixture

ID	Natural (NA)		Recycled (RA)		Magnetite (MG)
	0-2 mm	4-8 mm	0-5 mm	5- 9 mm	0-2 mm
AAC_M1	45%	55%			
AAC_M2		50%	25%		25%
AAC_M3			25%	50%	25%
AAC_M4			50%	25%	25%
AAC_M5	50%	25%			25%

As regards the characterization in the fresh state, the results are recommended in table 7.

Table 7: Fresh state concrete test results

	Slump Test		Air Content
ID	**Class/Slump mm**	**Spread mm**	**%**
AAC_M1	S5/>220	400	
AAC_M2	S2/70	110	
AAC_M3	S5/>220	500	5
AAC_M4	S5/<220	500	
AAC_M5	S5/>220	500	

The results of the data analysis showed that, except for mix 2, the addition of the high-density fine aggregate gives good workability and consistency compared to the natural aggregates taken alone. Furthermore, all the mixtures recorded an air content close to 5% and a rheological behavior similar to a self-compacting concrete (SCC).

Figure 3: Air content and slump test

As for the characterization in the hardened state, except for mix 1, prepared with natural aggregates only, all the mixtures showed comparable densities and compressive strengths close to 60 Mpa (Table 8).

Table 8. Hardened state concrete test results

ID	Cubic Compressive Strength				Density
	MPa				Kg/m^3
	3 days	7 days	28 days	58 days	average
AAC_M1	32.7	36.8	46.1	/	2262.2
AAC_M2	20.0	42.6	60.8	/	2700.0
AAC_M3	28.1	37.8	56.6	58.4	2646.0
AAC_M4	22.2	19.4	44.5	48.1	2614.2
AAC_M5	16.4	43.7	52.2	62.7	2613.0

3.2 AAM concrete mechanical characterization

The mix design chosen to build the foundation prototype was the one with prefixed mechanical and workability properties. Therefore, the Mix 5 was replicated four times in order to evaluate the repeatability of the results by modifying the percentages of water and mixing times, to optimize its rheological behavior in the fresh state and to evaluate further mechanical properties. The cubic and cylindrical compression resistance tests of the specimens were conducted according to UNI EN 12393-3. For each mixture, cylindrical specimens of 150 * 300 mm and cubic of 150 * 150 * 150 mm were prepared respectively. Three parallel specimens of each mixture were tested at the ages of 58 days to determine the average compressive strengths (During the experimental program it emerged that this type of mixture develops maximum resistance after about 60 days of curing). The indirect tensile strength was conducted according to the standard UNI EN 12390-6 on specimens of dimensions 150 * 300 mm. The mechanical characterization tests were performed with a 3000 kN hydraulic press equipped with support and compression plates having dimensions of 300 mm. In accordance with the above mentioned standards, the tests were performed under load control with a speed of 0.6 MPa/s.

Table 9: Mix 5 Optimization results

ID	Fresh State	Hardened State			
	Density	Slump Test	Cubic Compressive strength	Cylindrical Compressive strength	Indirect tensile strength
	Kg/m^3	Class/Spread [mm]	MPa	MPa	MPa
			58 days	58 days	58 days
AAC_M5	2940	S5>220 / 500	62.7	23.22	5.78
AAC_M5^{I}	2963		58.3	22.95	5.34
AAC_M5^{II}	2950		53.4	21.18	4.85
AAC_M5^{III}	2967		59.9	22.50	5.16
AAC_M5^{IV}	2964		60.1	22.78	5.89

Pending the results of the durability tests, the geo-conglomerate developed showed a good repeatability of the results, in addition to a good behavior in the fresh and hardened state. The compressive strengths of all the mixtures are in line with the results found previously, the cylindrical compression and indirect tensile tests have confirmed the goodness of the mix design with values comparable to those of an ordinary concrete.

3.3 SMART FRP rebar validation and calibration

Once the SMART FRP rebars were manufactured, the behaviour of FO sensors was investigated by means of tensile strength tests on SMART FRP rebars. Such tests were intended to validate and, eventually, calibrate the FO sensors. Smooth GFRP rebars were sensorized and tested on a ZwickRoell ProLine instrument with a 100 kN load cell. The tests were realized in displacement control mode with a rate of displacement of 0.5 mm/min. During the tests acquisitions with the OBR4600 system of Luna Innovations were run at predetermined ranges of value of load (i.e. 300-350 N; 600-650 N; 950-1000N). For each tested rebar the test was initially carried out until 5 kN load and repeated at least 3 three times. Then the test was repeated until 20 kN load.
To verify the proper operation of the FO sensors rebars were instrumented with 3 electric Strain Gages (SG) (uniaxial, 6mm length, 120 Ω resistance) each, that were connected to a MX1615B Quantum X module.
Figure 4 reports the strain values measured over the length of the FO for different applied loads, while figure 5 shows the FO signal acquired in comparison with the acquired data from SGs. Considering Figure 4 the value of the deformation read by the FO sensor is constant throughout the reading section and the effects of the adhesive are visible only nearby the glue position. In figure 5 the values of the FO strain signal recorded in the same SGs' positions on the rebars show a high agreement with SGs results demonstrating no need of calibration of the sensors.

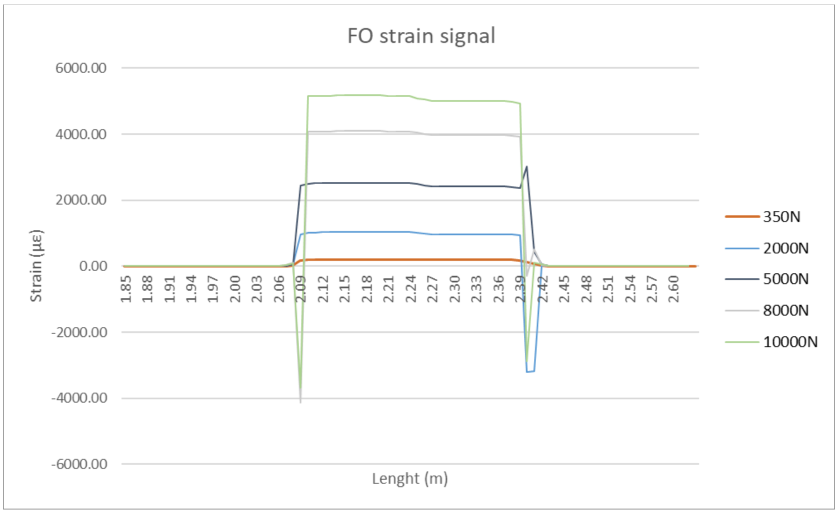

Figure 4: Strain values measured over the FO length for different loads.

3.4 SMART FRP rebar mechanical characterization: Compression tests

In order to validate the ability of the SHM system to monitor also compression stress, tests on concrete cubes with inside small segments of SMART rebars were realized (rebar length approximately 8 cm; embedded FO length approximately 6 cm). Different SMART

rebars inside the cubes were connected together by means of FO splicer to monitor more elements at the same time.
Tests were realized in a Controls Concrete Compression Testers machine with a load cell of 3000 kN on cubes of 150 x 150 x 150 mm3 following the UNI EN 12390-3 standard. The test was conducted in load control mode, that means that the machine controlled that the load applied to the sample was always coherent to the test, with a rate of 0.6 MPa/sec.

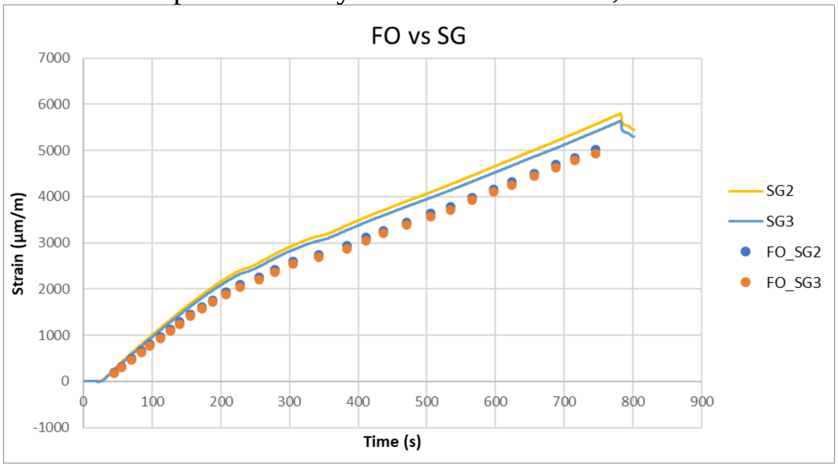

Figure 5: Comparison of FO and SG data

In Figure 6 it is possible to see how the different small SMART rebars inside the cube were able to detect increasing compression strain in the cube (100 kN – red line; 350 kN - yellow line; 600 kN – green line). Different values are due to not perfect alignment of the rebars inside the cube respect to the load surfaces.

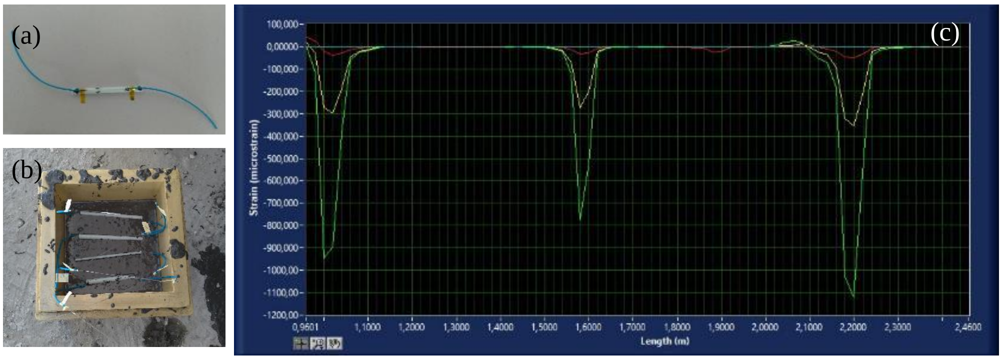

Figure 6: (a) SMART FRP rebar; (b) SMART concrete cube for compression tests; (c) Measured compression strain signals

3.5 SMART FRP rebar mechanical characterization: Adhesion tests

Adhesion tests on SMART specimen were realized. The direct pull-out tests setup and specimens are designed according to the RILEM Recommendations “RC 6 Bond test for reinforcement steel. 2. Pull-out test, 1983”. Each specimen is cubic with side equal to 10 cm and a centred embedded rebar in order to have a concrete cover equal to 4.5 cm. The embedded rebar had two different zones over its length: the bonded zone, where the concrete is able to adhere to the rebar, and the unbonded zone, where the concrete isn’t able to adhere to the rebar. The unbonded zone was realized by applying a plastic sheet on the specific length of the rebars.
Three LVDTs (Linear Variable Displacement Transducer) are used: one is anchored at the unloaded side of the bar meanwhile the other two are positioned at the loaded side to

record the corresponding slips. A tensile force is applied by means of a testing machine under displacement control at a rate of 0.2 mm/min. All tests are stopped when a free slip of 10mm is reached, except when the specimens failed before (i.e., splitting failure). The results presented on Figure 7 demonstrate that FO sensors not only can survive the concreting process, but can also acquire strain measurement. In particular, in the graph it is clear the ability of FO sensors to detect increasing tensile strain in the specimen as the load increases. (3 kN – red line; 10 kN - yellow line; 15 kN – green line).

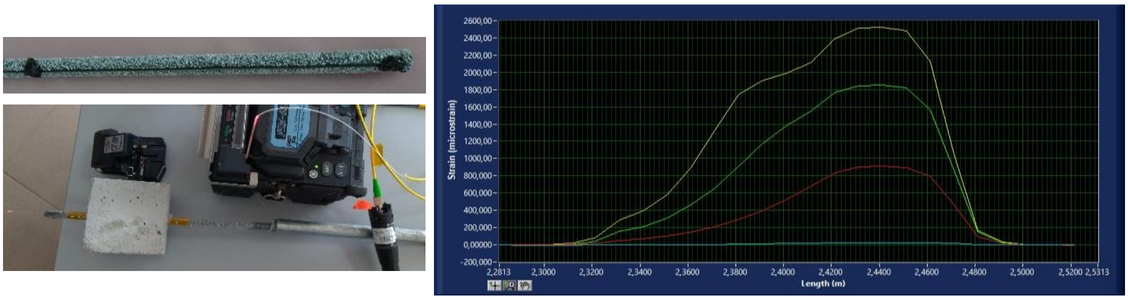

Figure 7: (a) Smart rebar; (b) Pull-out specimen proving the FO survival; (c)Measured FO strain signal

4. CONCLUSIONS

This study deals with the development of a high durable solution for marine structures composed of sustainable concrete formulations, combining mineral aggregates with glass powder and blast furnace slag (instead of ordinary cement) activated with alkaline materials, and a structural health monitoring system based on SMART FRP rebars.

Based on the study carried out, cementless formulations suitable for production of structural elements have been optimized. This can be regarded as a positive result especially considering that, the cement content is zero and, furthermore, allows to give a second life to the blast furnace slag. These results are obviously linked to the evaluation of the durability of the geoconglomerate because, despite the good mechanical performance shown so far, it is a decisive parameter for the performance of a concrete, especially if intended for marine use.

Regarding the SHM system for concrete structures, the reported activities showed the feasibility of FO distributed sensors to be applied as monitoring system in reinforced concrete structures. Being applied to FRP rebars, that overcome any potential durability problems related to steel corrosion, such solution increases the durability of the structure and, implemented as a real-time monitoring system, permits a continuous evaluation of the structure health, thus reducing maintenance costs.

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