SEACON Project: sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement

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Abstract. This paper shows goals and preliminary results of the SEACON research project. SEACON deals with the production of innovative concretes, containing high-chloride constituents (i.e. cement, water and aggregates) in combination with non-corrosive reinforcement. This study is being undertaken through a transnational cooperation among several industrial partners and two academic institutions from Italy and USA, under the aegis of the EU program called "Infravation". The project aims to prove the feasibility of a new reinforced concrete technology, by investigating three primary aspects: mechanical performance, environmental impact, and durability of the final reinforced concrete product.

With reference to the characterization of concrete, constituents were first investigated using the most common chemical and physical tests. Accordingly, different concrete mixtures were produced using seawater, salt-contaminated aggregates, and a combination of innovative cements and commercially available fly ash. The mixtures were tested for both fresh and hardened concrete properties, and the results were assessed. Environmental analyses on elutes were performed to assess the leaching of chloride and other elements. Furthermore, the resistance to different degrading agents was investigated (i.e., sulfate attack and alkali-aggregates reaction). The investigation of durability of the system will include selection and evaluation of the best reinforcement alternative to traditional "black" steel reinforcement. Reinforcing bars, made of boron-free E-CR glass fibers embedded in a vinyl ester resin (GFRP), and stainless steel bars (SSR) will be considered to achieve the desired service life of a structure exposed to marine environments or de-icing salts.

Based on the results obtained from laboratory investigations, two field demonstrations will be performed at the end of the project, one in Italy and one in Florida. The resulting structures will be monitored during their service life even beyond the SEACON project duration to demonstrate the feasibility of the technology.

Introduction

As the construction industry continues to recognize the importance of a sustainable development, many research works are going in this direction with the aim to improve the performance of construction materials and construction techniques with reduced environmental impacts.

Focusing on concrete, the most used man-made product in the building industry, three negative aspects, related to its production and use, have to be considered when environmental protection is assessed: (I) the use of high amounts of raw materials, resulting in the decrease of available natural sources; (II) the consumption of high amount of energy for the production, transport, use of raw and final materials; (III) the creation of large volumes of old concrete from dismissed structures (demolition waste) [1].

Concrete is basically constituted by water, aggregates and cement: an interesting challenge is to figure out how to procure each of these components reducing the use of natural resources and the consumption of energy.

The amount of fresh water involved in the concrete industry (washing aggregates and mixing/curing concrete) sets around several billion tons. According to the World Meteorological Organization,

more than half of the world's population will lack sufficient drinking water by 2025 [2]: hence, the need of limiting the consumption of fresh water is vital for a sustainable future.

One of the possible alternatives is the use of seawater, an appealing solution especially in those countries where no other source of water is available or where freshwater is costly to transport [3]. The use of seawater has been widely investigated for several decades, giving contradictory results, particularly for what concerns strength development [3,4,5,6]; on the other hand, the effect on fresh concrete properties are commonly recognized (i.e. reduction of setting times [7]) and must be considered when the mix design is formulated.

Recycled concrete as aggregate is gaining more and more importance, since construction and demolition waste represents around 31% of all the waste produced in the European Union [8]: recycled concrete aggregates (RCA) are commonly used in partial replacement of natural aggregates [9,10,11], even if the quality of RCA can significantly vary depending on the different source. A wide amount of RCA derives from demolition of infrastructures, especially bridges, pavements, parking garages and piers: in these cases, the resulting aggregates were probably subjected to chloride penetration due to exposure to de-icing salts or to marine environment. Therefore, an accurate characterization is required since the chemical and physical features of RCA can strongly affect the properties of the final concrete [1].

Sustainability in the cement production field can be fronted through two different ways: on one hand the use of alternative fuels (such as Waste Derived Solid Fuels – WDSF) during the clinker production in order to reduce the consumption of fossil fuels; on the other hand, the use of supplementary cementing materials (SCM), such as by-products deriving from different industrial production (by-pass dust, fly ash, bottom ash to name a few). Similarly to what above argued for aggregates, even in this case the variability of the materials involved in the clinker/cement production can deeply influence the properties of the final product. The greatest obstacle to their application in traditional concrete is due to the high level of alkali chlorides and soluble metal salts, whose amount in cement is regulated by specifications and codes.

In most instances, the use of seawater, chloride-contaminated aggregates, and high-chloride content binders is forbidden because of the associated risk of corrosion of steel reinforcement. Indeed, chlorides are harmful to the durability of reinforced concrete (RC), since they induce corrosion of conventional "black" steel reinforcement. In order to avoid serious corrosion-induced damages and consequent expensive repairs, RC is normally designed to avoid chloride-contamination of raw materials and to prevent, to the extent possible, chloride penetration throughout the expected service life. However, technologies developed over the last two decades have facilitated the use of non-corrosive reinforcing bars to replace black steel reinforcement for concrete when the durability of a structure is of concern [12,13].

The research project "SEACON: Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement" (http://seacon.um-sml.com) addresses the issue of sustainability from the perspective of producing an innovative concrete based on environment-friendly components. Within the framework of ERA-NET Plus Infravation 2014, an infrastructure innovation program on "Advanced systems, materials and techniques for the next generation infrastructure" (http://www.infravation.net/), SEACON is a 2.5-years project started on October 1, 2015, that is being carried out by a transnational consortium of six academic and industrial partners, including Buzzi Unicem.

The goal of SEACON is to promote the use of best practices in both the production of concrete and RC structures by implementing alternative materials. The aim is to reduce the use of critical resources by replacing them with chloride-contaminated alternatives coupled with non-corrosive reinforcement. This approach will extend the longevity and durability of the constructed elements under aggressive environmental conditions. The overarching objectives of this research program are:

- to confirm scientific evidence, through experimental work, that the presence of chlorides is not harmful to the properties of plain concrete (i.e., workability, strength development, durability);

- to assess through LCA and LCC durability performance and economic impact resulting from the use of chloride-contaminated aggregates, high-chloride content cement, and seawater on structural concrete;
- to prove, through laboratory investigations, the successful use of Fiber Reinforced Polymer (FRP) bars made with glass fibers embedded in a polymeric resin matrix and Stainless Steel Rebars (SSR) as reinforcement in concrete made with seawater, salt-contaminated aggregates, and high-chloride content cement;
- to demonstrate this technology by means of two real-size field prototypes, incorporating commercial design, while developing model specifications and guidelines to be proposed for adoption to national and international standard-writing agencies.

The main purpose of this part of the work is the comparison between innovative concretes, made with unconventional ingredients, and those made with traditional components, to show that it is possible to change the current perspective of limiting the chloride content in concrete. The use of proper types of corrosion resisting rebar may allow to produce concrete regardless the amount of chloride of its components using: (I) cements without restrictions on the chloride content; (II) chloride-contaminated RCA, in partial replacement of natural aggregates; (III) seawater instead of freshwater.

In this paper, the influence of the use of alternative components on the fresh, hardened and durability properties of the final concrete has been investigated in comparison to an ordinary reference concrete. The results reveal a strong variation in the fresh properties, requiring further investigation on maintaining workability, while for what concerns compressive strength, only a slight decrease in the long-term performance has been observed. Interestingly, the use of RCA improves the compressive strength with respect to the reference concrete produced with natural aggregates. Durability investigations reveal that in most cases, the use of seawater stresses the effect of degrading agents on the concrete since it greatly contributes to the amount of chloride. In general, the presence of chloride-contaminated components seems to aggravate the durability loss due to the osmotic exchange phenomenon that occurs between the concrete and the environment. The experimental study showed, in particular, the need of making some changes to the testing procedures used to make them more representative of the mechanisms that occurring with these mixtures.

Experimental investigation

   Materials. All the raw materials needed for the experimental investigation were selected and characterized. A limestone Portland cement (reference cement), widely used for structural applications in Italy (66% of the market share), which consists of 84% Portland cement clinker, 10.3% ground limestone and 5.7% gypsum, was considered as reference. The strength class of this cement is 42.5 MPa and according to European standard EN 197 it is designated as: CEM-II/A-LL 42.5R. A cement (SEACON cement), with a high amount of chloride ions, was specifically produced for this project. This cement has a composition similar to the reference one, but the ground limestone was replaced by a chloride-contaminated limestone from industrial waste. The SEACON cement cannot be considered conforming to EN 197-1, due to the chloride content that exceeds the threshold of 0.1%. Fly ash was also used in all the concrete mixtures, in order to reduce the porosity and limit the mobility of ions. Table 1 reports the mineralogical composition of the two cements determined by quantitative XRD Rietveld analysis.

SEACON cement contained a higher amount of free lime if compared with the reference cement, due to the high content of this element present in the chloride-contaminated limestone. Also the amount of portlandite (calcium hydroxide, $Ca(OH)_2$) and langbeinite (magnesium/potassium sulfate, $K_2Mg_2(SO_4)_3$) was greater in SEACON cement than in the reference one.

A chemical analysis (UNI EN 196-2), obtained through XRF spectrometry, was carried out on cements and fly ash (Table 2). The most interesting value is the chloride content that represents the major difference between the two cements.

Table 1- Mineralogical composition determined by quantitative XRD Rietveld analysis of reference cement and SEACON cement

wt.%	Reference cement	SEACON cement
C_2S	11.29	14.07
C_3S	55.93	53.14
C_3A	4.38	3.33
C_4AF	9.61	9.52
Periclase (MgO)	1.66	2.04
Free lime (CaO)	**0.30**	**4.25**
Gypsum ($CaSO_4 \cdot 2(H_2O)$)	3.25	3.77
Calcite ($CaCO_3$)	8.64	3.02
Dolomite ($MgCa(CO_3)_2$)	1.19	0.73
Quartz (SiO_2)	0.41	1.45
Arcanite (K_2SO_4)	2.02	1.53
Langbeinite ($K_2Mg_2(SO_4)_3$)	**1.14**	**2.04**
Portlandite ($Ca(OH)_2$)	**0.18**	**1.11**

Table 2- Chemical composition of the investigated binders

wt.%	Reference cement	SEACON cement	Fly ash
LoI	5.87	3.85	5.62
SiO_2	18.35	19.00	56.58
Al_2O_3	4.27	4.53	26.22
Fe_2O_3	3.04	3.23	5.41
CaO	60.88	60.90	1.49
MgO	2.74	2.78	0.85
SO_3	3.33	3.68	0.07
Na_2O	0.24	0.28	0.42
K_2O	0.88	1.19	1.77
TiO_2	0.19	0.20	-
Cl$^-$	**0.02**	**0.23**	-
M.E.	0.19	0.21	1.57

Table 3 shows the results obtained through physical tests performed on the two cements according to current standards. The main difference between them is their reactivity; in fact, SEACON cement presents shorter setting times.

Both natural and recycled aggregates were used; as natural aggregates two siliceous sands (0-2 and 0-4 mm) and a gravel (4-12.5 mm) from Torrazza concrete plant (TO) were employed.

In order to simulate a highly chloride-contaminated RCA, old specimens stored from previous researches were utilized. About 200 kg of chloride-contaminated concrete, made with Portland cement (w/c = 0.5), crushed limestone aggregates and chloride contamination ranging from 1% to 5% by mass of cement, were crushed and sieved to obtain a 4- 12.5 mm diameter fraction.

Physical data of all the aggregates used are shown in Table 4. It is worth to notice the very high water adsorption measured for the RCA with respect to the other materials.

Eluate analysis was performed on RCA to evaluate the possible release of chloride and sulfate from the aggregate into water. After a 15 minutes-stay of the material under stirring in deionized water, the values of the chloride and sulfate contents, found by means of ionic chromatography, are respectively 0.39 g/l and 0.03 g/l.

Table 3– Physical tests on reference cement and SEACON cement

Physical tests		Units	Reference cement	SEACON cement
Setting times (UNI EN 196-3)	Water	[%]	28.6	28.4
	Initial setting time	[min]	**210**	**140**
	Final setting time	[min]	**310**	**220**
Laser granulometric analysis	Residue to 8 µ	[%]	74.2	73.1
	Residue to 24 µ	[%]	38.1	38.9
	Residue to 40 µ	[%]	12.6	15.2
Specific gravity (UNI EN 196-6)		[g/cm^3]	2.98	2.98
Blaine fineness (UNI EN 196-6)		[cm^2/g]	3220	2805
Flow (UNI EN 1015-3)		[%]	99	83
Compressive strength (UNI EN 196-1)	2 d	[MPa]	26.3	26.2
	7 d	[MPa]	39.4	38.7
	28 d	[MPa]	52.2	48.7

Table 4 – Physical tests on natural aggregates and RCA

	Unit	Sand 0-2 [mm]	Sand 0-4 [mm]	Gravel	RCA
Water absorption (UNI EN 1097-6)	[%]	1.0	1.0	1.0	**5.3**
Density (UNI EN 1097-6)	[kg/m^3]	2690	2680	2740	2574
Moisture (UNI EN 1097-5)	[%]	4.3	4.6	2.5	2.0

Fresh water and natural seawater, collected from the Mediterranean Sea near Cogoleto (GE, Italy), were used. Table 5 reports the elements contained in the waters, measured through ICP-OES, and the chloride content determined through titration according to Mohr (Chloride in water) with $AgNO_3$.

Table 5- Analysis of fresh water and seawater through ICP-OES and titration

Water	Concentration [mg/l]										
	Al	Ca	Fe	K	Mg	Na	S	P	Li	Si	Cl$^-$
Fresh water	<0.10	103	<0.10	2.6	14	20	12	<0.10	n.n	8.9	71
Seawater	0.19	**483**	<0.10	**377**	**1455**	**11766**	**1037**	<0.10	0.22	0.68	**20898**

Table 6- Concrete mixture proportions

Ingredients	Units	Mix A	Mix B	Mix C	Mix D
Reference cement	[kg/m^3]	335	-	335	335
Fly ash	[kg/m^3]	30	30	30	30
SEACON cement	[kg/m^3]	-	335	-	-
Fresh water	[l/m^3]	175	175	-	180
Seawater	[l/m^3]	-	-	175	-
Sand 0-2 mm	[kg/m^3]	493	493	493	489
Sand 0-4 mm	[kg/m^3]	600	600	600	596
Gravel 4-12.5 mm	[kg/m^3]	744	744	743	369
RCA	[kg/m^3]	-	-	-	347
Superplasticizer	[kg/m^3]	3.2	4.1	3.5	3.5
Retarding agent	[kg/m^3]	-	-	0.8	-

Concretes. The optimization of the design of four concretes was pursued, based on the best rheology achievable, in order to reach a desired compressive strength (40 MPa at 28 days of curing) and consistency (consistency class S4 according to UNI EN 206 standard so a slump between 16

and 20 cm). A specific superplasticizer was selected and a set retarding agent was used to compensate the known accelerating effect of chlorides.

In Table 6 the mixture proportions for the four types of concrete are presented.

Methods. A hydration study was performed, through XRD analysis, on the cement pastes (reference cement + fresh water; SEACON cement + fresh water, and reference cement + seawater) using a w/c ratio of 0.5, in order to determine the evolution of the mineralogical phases assemblage during time and to evaluate the possible effect due to seawater salts on hydration kinetics.

The cements were hydrated and the pastes were submitted to XRD analysis from the beginning to 28-days curing; TiO_2 –anatase was added 4% in weight on the binders as internal standard.

The four different concrete mixtures produced were characterized considering fresh and hardened concrete properties, and resistance to concrete degradation considering the possible mechanisms (drying shrinkage, sulfate attack, and alkali-aggregates reaction). Each batch of concrete was characterized in the fresh state by means of the air content (UNI EN 12350-7), the fresh density (UNI EN 12350-7), and the slump test (UNI EN 12350-2) immediately after mixing and one hour later to prove the maintenance of the workability.

After casting, cubic specimens 15x15x15 cm were cured in a moist room (20°C and 95% of RH) until the compressive strength test (UNI EN 12390-3) was performed at different curing times (24 hours, 7, 28 and 90 days) to determine the strength development.

The drying shrinkage of the four concrete mixtures was tested according to the UNI 11307 on beams 10x10x50 cm, to understand if the chloride content can affect the shrinkage behavior.

The effect of sulfates was tested according to the SVA Flat Prism Method testing the expansion of mortar samples 16x4x1 cm immersed at age of 14 days in a 4.4% Na_2SO_4 solution at 5°C and 20°C. For this test, mortars were produced as follows:

- Mix Reference: standard mortar (450 g of cement, 1250 g of normalized sand, and 225 g of fresh water according to UNI EN 196-1) using the reference cement;
- Mix SEACON: standard mortar with SEACON cement;
- Mix Seawater: standard mortar with the reference cement and substituting freshwater with seawater;
- Mix RCA: standard mortar with the reference cement substituting the normalized sand with the RCA suitably grinded and sieved.

Moreover, in order to evaluate the effect of sulfate attack on the mineralogical composition, selected pastes were prepared and subjected to an internally developed test[1].

The presence and effect of alkalis were tested according to the Italian Standard UNI 8520-22; the test was adjusted in order to test the reactivity of different kinds of aggregates in combination with the two different cements and water sources. The test has to be conducted on mortars made with 400 g of cement, 900 g of aggregates, divided into five special grain sizes, and 188 g of water. Reference cement, SEACON cement and seawater were tested in combination with both unreactive (N.R.) and reactive (R.) aggregates. In addition, the reference cement was tested in combination with RCA.

The eluate analysis was performed on the four concrete mixtures in order to assess the leaching of the main elements (chloride and sulfate) according to the DAfStb-guidelines, Tank test (ref. Grundsätze zur Bewertung der Auswirkungen von Bauprodukten auf Boden und Grundwasser, pag. 58, Table II-A.3). This test is important to evaluate if the concretes made with high chloride and sulfate content ingredients could cause corrosion problems in adjacent ordinary steel reinforced concretes.

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[1]14 days old pastes were treated with a 4.4% Na_2SO_4 solution for four days (paste:solution = 20:100), dried under nitrogen at 40°c for 24 hours and analyzed by means of TG/XRD.

Experimental results and discussion

Hydration study. Fig. 1 represents the mineral phase assemblage variation of the pastes during the hydration process as measured by XRD-Rietveld analysis.

The hydration of the reference cement with fresh water, Fig. 1a, consists in the formation of portlandite, in very high amount, and ettringite from the beginning; a wide amount of amorphous phase (mainly calcium silicate hydrates) is detected. The same happened also considering SEACON cement with fresh water, Fig. 1b, but the amount of ettringite produced is higher than in the previous case, while a reduced content of portlandite is measured. The use of seawater, Fig 1c, thanks to the presence of carbonates and chloride ions, causes the formation of AF_m phases, hemicarbonate $(C_4A\bar{C}_{0.5}(OH)^-_{0.5}nH)$ and calcium-chloroaluminate phases $(C_4ACl_2H_{10}$, known as Friedel's salt). This is probably due to the lack of sulfate needed to produce a higher amount of ettringite (AF$_t$ phase: $C_6A\bar{S}_3H_{32}$) [14].

Overall, a slowing in the hydration kinetics of the pastes produced with SEACON cement and seawater can be observed, with respect to the reference cement with fresh water, on the other hand, the amount of amorphous phase and of the residual anhydrous clinker is very similar in all the samples revealing that the activity of the most reactive phase (C$_3$S) is only slightly affected by the presence of chloride.
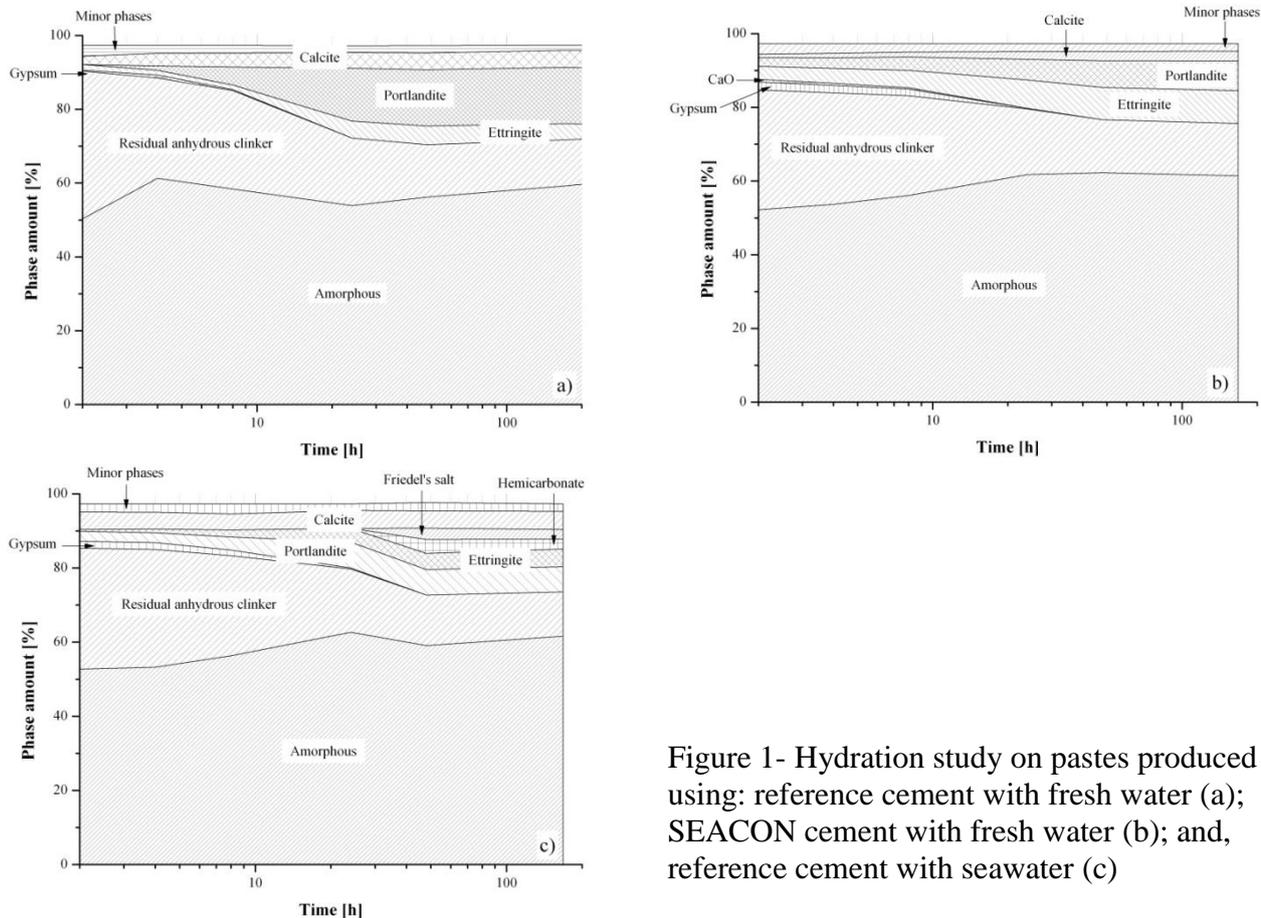

Figure 1- Hydration study on pastes produced using: reference cement with fresh water (a); SEACON cement with fresh water (b); and, reference cement with seawater (c)

Fresh concrete. Table 7 reports the test results on the fresh concretes. The fresh density values range from 2,372 to 2,414 kg/m^3. Mix D exhibits the lowest value due to the minor density of RCA equal to 2,574 kg/m^3 compared to 2,740 kg/m^3 of the natural gravel.

The voids content values do not change significantly from a mix to another.

The slump test values demonstrate that all the mixtures exhibit a consistency in complying with the provisions of the consistency class chosen (160-210 mm). Nevertheless, most of the mixtures do not maintain the workability over time. In fact, the values measured one hour after initial mixing are rather reduced compared with those measured at the mixing time, in particular as regards to Mix D,

due to the high water absorption of RCA. Accordingly, a more accurate study on the use of specific admixtures will be performed to extend the workability.

Table 7- Fresh concrete properties

Fresh properties		Units	*Mix A*	*Mix B*	*Mix C*	*Mix D*
Air content (UNI EN 12350-7)		[%]	2.3	1.9	1.9	2.1
Fresh density (UNI EN 12350-6)		[kg/m^3]	2411	2414	2404	2372
Slump (UNI EN-12350-2)	t=0	[mm]	180	210	170	175
	t=60 min	[mm]	155	170	120	40

Hardened concrete. Fig. 2 shows the strength development of the four mixtures up to 90-days measured according to the UNI EN 12390-3. At 28-days, all mixtures overcome the design target value of 40 MPa. Interestingly, the use of RCA favors a development of higher strengths with respect to the other formulations; the use of SEACON cement and seawater slightly decreases the long-term compressive strengths.
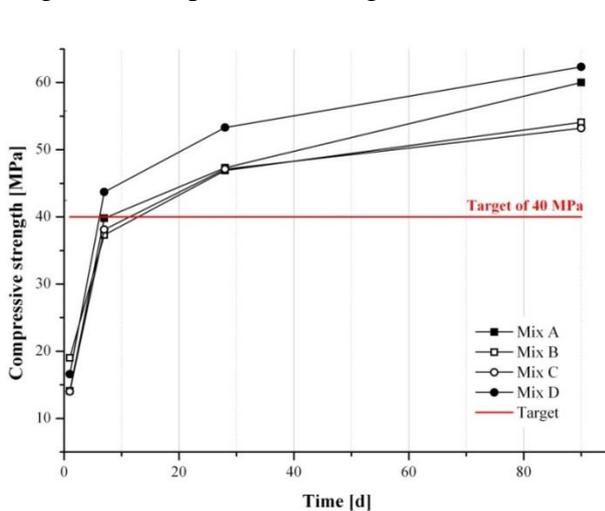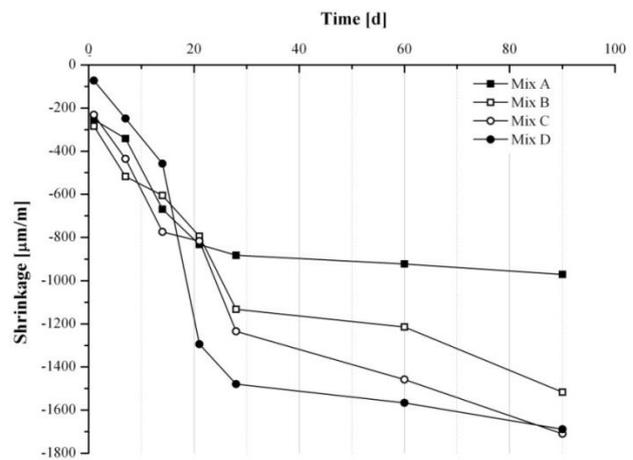

Figure 2- Compressive strength results

Figure 3- Drying shrinkage of concretes

Resistance to degradation.

Drying shrinkage. In Fig. 3 the evolution of drying shrinkage of the different concrete mixtures is shown. Considering Mix A as reference, it is clear that the addition of high chloride content ingredients (SEACON cement, seawater and RCA) has negative effects causing the increase of the shrinkage values and reaching -1600 μm/m after 90 days for Mix C and Mix D.

This behavior can be related to an effect induced by the higher surface tension of the pore solution when oversaturated in salts (mainly chloride), which causes an enhanced tendency to shrinkage. This effect is probably mitigated in a chloride rich environment, such as harbor or seacoast.

Sulfate resistance. Fig. 4 demonstrates that the presence of chloride ions, in particular if seawater is used as mixing water, aggravates the expansion due to sulfate attack: "Mix SEAWATER" shows the worst results both at 5 and 20°C, reaching 4000 μm/m after 90 days and not allowing to continue further with the measures. The other three mixtures show better results at 20°C, but at 5°C the expansion was too high (Fig. 5b and c) or the conditions of the samples too bad (Fig. 5a and d), to allow making further measures in all the cases after 90 days.

The expansion detected during the test could be explained considering that there is a strong osmotic pressure since the pore solution of concrete is oversaturated in chloride ions and the environment is rich in sulfates: chloride ions are pushed into the external solution and sulphate ions are attracted inside the concrete resulting in a higher damage. Fig. 6 shows what happened in a paste made with reference cement and seawater, the most interesting case, when sulfates are provided: the drastic decrease of portlandite and the entire dissolution of Friedel's salt result in the formation of a great amount of ettringite. The worse behavior recorded at 5°C is instead ascribable to the formation of

thaumasite ($C_3S\bar{S}\bar{C}H_{15}$), as shown in Fig. 7 [15] (XRD patterns have been obtained by partial removal of sand after crushing and sieving on the mortars samples at the end of the sulfate resistance test).
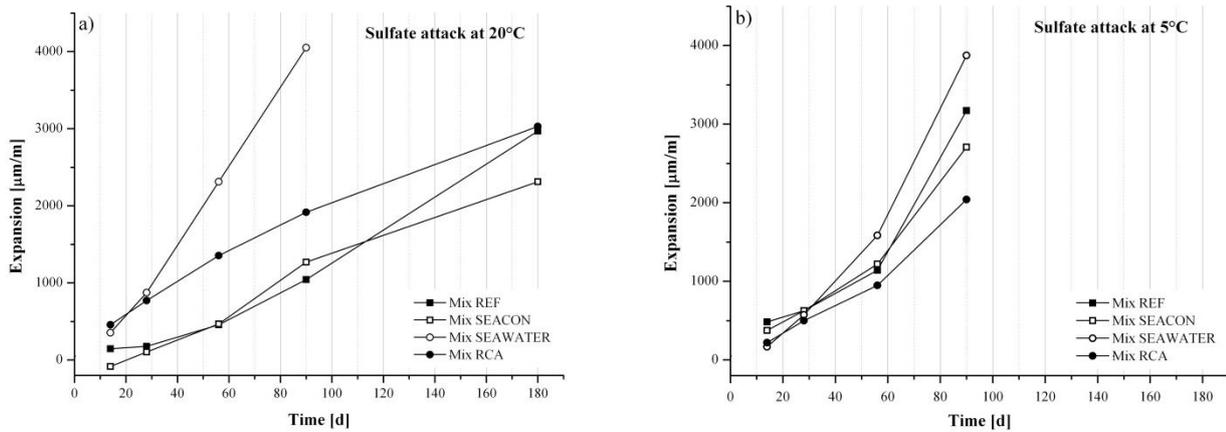

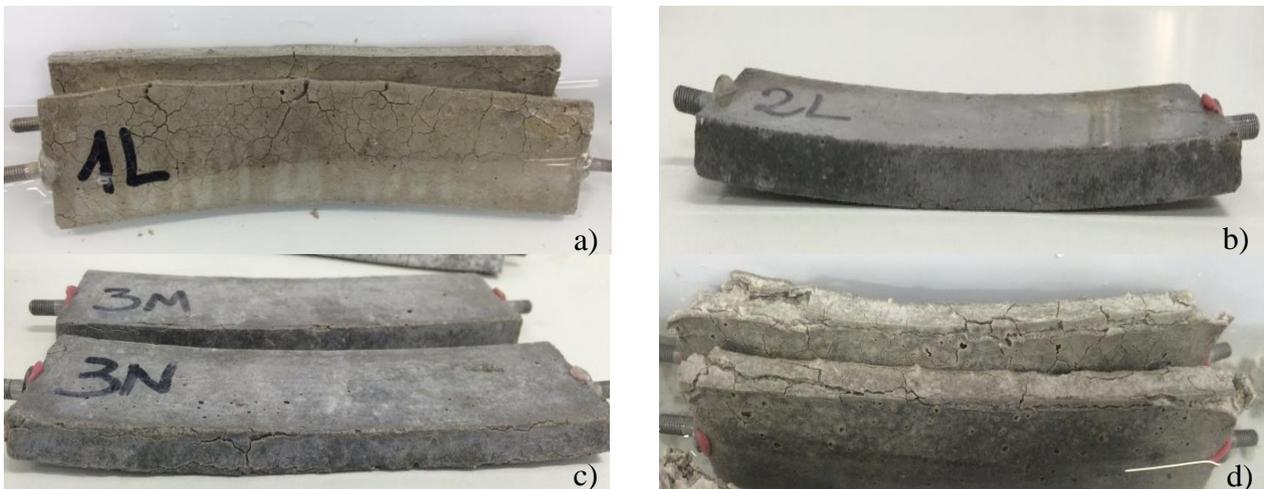Figure 4- Sulfate resistance test performed at 20°C (a) and 5°C (b)

Figure 5- Specimens of Mix REF (a), Mix SEACON (b), Mix SEAWATER (c), and Mix RCA (d) after 180 days of sulfate attack at 5°C
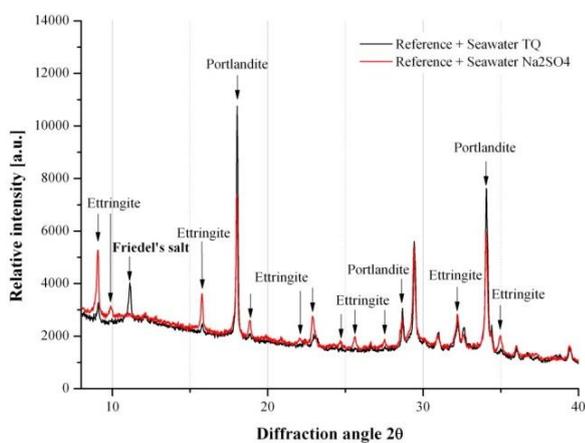

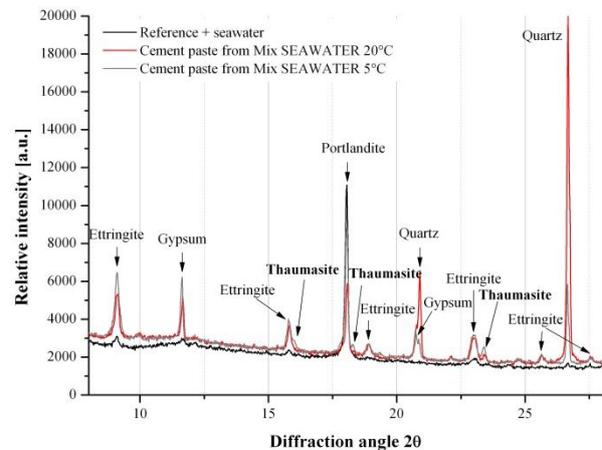Figure 6- Sulfate attack on pastes made with reference cement and seawater

Figure 7- XRD results on cement pastes obtained from mortar samples after sulfate resistance test (Mix SEAWATER)

Alkali-aggregates reaction test (AAR). The results of the AAR test, Fig. 8, indicate that the presence of alkali and chloride in concrete has a worsening effect on AAR expansion. The preliminary expansion values, after only three months from the beginning of the test, do not seem to be dependent on the nature of the aggregates; in fact, they are similar for mixtures with reactive and unreactive aggregates. The worse behavior is recorded for the mortar prepared with the SEACON cement, but this effect is probably not linked to an AAR phenomenon rather than to the higher free lime content of the SEACON cement that causes an higher expansion in the 100% moist environment compared to the one of the reference cement (Table 1).

When RCA is used, the expansion significantly increases in comparison with the use of the other two types of aggregates, but it is still better than SEACON cement and seawater.
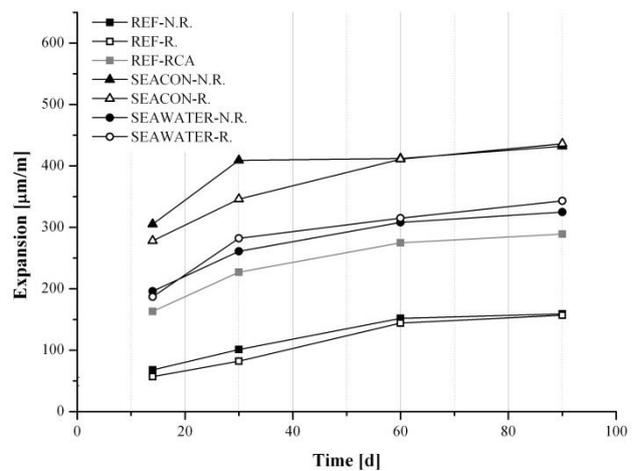
Figure 8- Alkali-aggregate reaction test

Eluates. Fig. 9 reports the cumulative chloride and sulfate amounts released at different times (1, 3, 7, 16, 32 and 56 days) for all the investigated concrete mixtures. The eluate results highlight that the presence of chloride-contaminated components inevitably leads to the release of chloride in the contact solution. The mixture produced using seawater releases the greatest amount of chloride, Fig. 9a, continuing until the end of the test. Besides, mixtures containing SEACON cement and RCA release moderate amounts of chloride, in particular at the beginning. It must be taken into account that the overall amount of chloride in the concrete mixture is much higher in the Mix C, due to the contribution of seawater. Fig. 9b shows that the release of sulfate does not take place in the concrete made with SEACON cement nor in the concrete prepared with seawater, while a low amount is released by the other two systems. In the case of Mix C, a possible explanation can be supplied considering the ionic exchange between chloride, released in a very high amount, and sulfate, stored in the cement paste in replacement of chlorides. In Mix B, sulfates are strongly bound inside the ettringite structure, as demonstrated by the hydration study, revealing that the amount of ettringite is higher in this formulation than in the others(Fig. 1b).
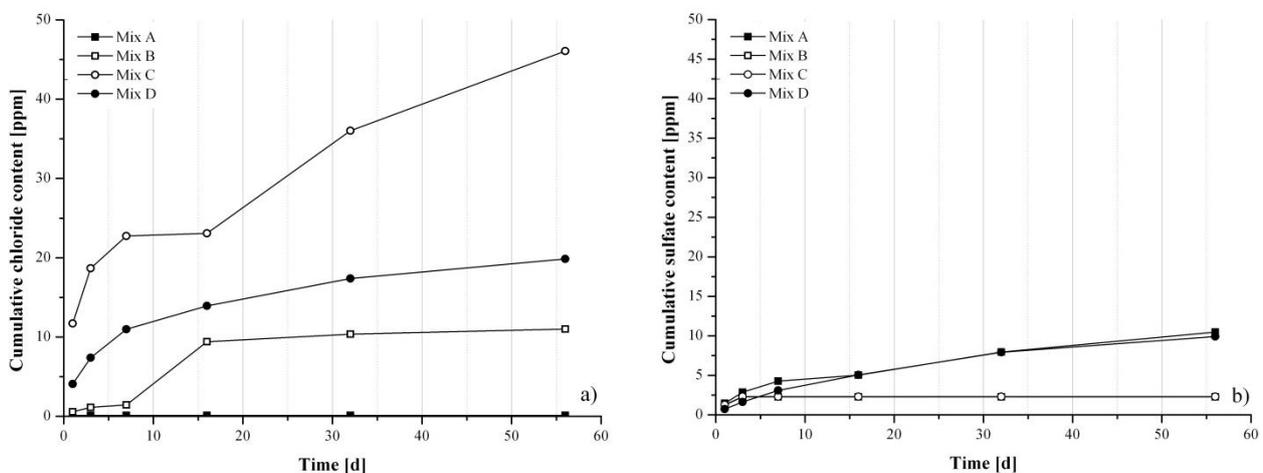
Figure 9- Cumulative chloride (a) and sulfate (b) releases determined through ionic chromatography

Conclusions

The SEACON project intends to demonstrate the feasibility of concrete made with high-chloride cement, seawater, and salt-contaminated aggregates for the production of durable and economical structures when combined with non-corrosive reinforcement.

This paper focused on the experimental investigation performed in order to produce and test concrete mixtures made with unconventional raw materials contaminated by chlorides. Additionally, an ordinary concrete mixture produced with traditional components was produced as reference. Above all, the main goal of this study has been the understanding of the effect of chloride-contaminated components on concrete, in terms of fresh, hardened and durability properties. The results obtained can be summarized as follows.

First, a strong variation in the fresh properties, in particular using seawater and RCA in mixture, has been detected requiring further investigation on maintaining the workability. On the contrary, for what concerns compressive strength development, only a slight decrease in the long-term performance has been observed. Interestingly, the use of RCA improved the compressive strength with respect to the reference concrete produced with natural aggregates.

The presence of high amount of chloride in concrete caused an increase of shrinkage. This behavior can be related to an effect induced by the higher surface tension of the pore solution when oversaturated in salts (mainly chloride), which causes an enhanced tendency to shrink. This effect would have probably been mitigated if the concrete had been exposed in an environment rich of chloride, such as coastal area. The understanding of this phenomenon will be part of the future work. The preliminary expansion results from the alkali-aggregates test showed that there is no dependence on the type of aggregates. In fact, in both the cases of reactive and unreactive aggregates the mixtures presented expansion values depending on their alkali and chloride content. The use of SEACON cement showed the worst performance, but this effect is probably not linked to an AAR phenomenon rather than to the higher free lime content of the SEACON cement that causes an higher expansion in the 100% moist environment compared to the one of the reference cement. All samples were strongly affected by the sulfate attack. The expansion detected during the test could be explained considering that there is a strong osmotic pressure since the pore solution of concrete is oversaturated in chloride ions and the environment is rich in sulfates: chloride ions are pushed into the external solution and sulphate ions are attracted inside the concrete resulting in a higher damage. The test will be repeated using a sulfate-resisting cement, in order to better understand the contribution of the different components. Elution test evidenced that there is a potential risk of leaching of chloride from seawater concrete, additional investigations must be carried on in order to more deeply analyze the release mechanism.

In general, it was demonstrated that the use of seawater in concrete could cause the worst performance in terms of durability since it brings a high chloride content. Nevertheless, the final destination of a concrete made with seawater would probably be a marine environment, thus rich in chloride: the high salt concentration in moisture would mitigate the osmotic exchange effect above described.

It must be pointed out that the laboratory procedures used for testing the durability behaviors of these chloride-contaminated concretes are almost certainly not the most appropriate. Therefore, further tests are needed in order to understand which precautions, in terms of choice of the type of cement, selection of aggregates, curing conditions, and possible additions, should be taken in order to produce a durable and dimensionally stable concrete using seawater.

Acknowledgements

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