



performance evaluation of repair systems and products

# TECHNICAL REPORT



**TR 7.2**

REPAIR SYSTEMS IN SMALL SCALE SAMPLES  
EXPOSED IN EXPERIMENTAL SITES



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**NOTE:**

*The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented.*

## PREFACE

The main subjects concerned in this TR were discussed and a general review was made inside the working group WG A7 – Performance evaluation of structural materials and new repair products. The WG was created in the DURATINET project with the aim to evaluate the adequacy of repair materials and new repair products.

This TR describes the behaviour of concrete sample submitted to marine environment in two experimental sites: La Rochelle site (France) and Saint Nazaire site (France), with the aim to analyse the performance of concretes and repair products in these environments.

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## 1 Introduction

In this report, the behaviour of concrete sample submitted to marine environment is presented. Two experimental sites are tested: La Rochelle site (France) and Saint Nazaire site (France). The objective of this report is to analyse the performance of concrete and repair materials in these environments.

We have to note that all the sites were used in a previous European project 'MEDACHS'. For the first site, concretes were tested according to carbonation and chloride tests. In La Rochelle and Saint Nazaire sites, concretes and repair products are tested according chloride ingress.

## 2 Study of concrete small samples in La Rochelle site

### 2.1 Characterization of experimental site

The experimental site of La Rochelle is located at the old harbour in downtown, near the St Nicolas's tower. It is one of the two towers showing the entrance of the harbour with the Lantern's tower. This site offers the possibility to expose samples on a 500 m<sup>2</sup> inclined area. Most of the samples are simply put on the place. However, by the last year, the laboratory LEPTIAB (La Rochelle University) used a process to keep the concrete samples straight in place in spite of the tide effect. In order to picture our purpose, we show on photographs (Fig. 1) the experimental area on low and high tide for a 75's coefficient.



*Fig. 1. Experimental tide zone site of La Rochelle*

On this area, the tide cycle is approximately of 6 hours from low to high tide with a 6,00 meters maximal height. This experimental area is exactly located in the middle of the low and high level of the tide, as shown in figure 2. By this fact, every sample is exposed to the dry and wet cycle zone every time of the year.

In a 24 hours lapse, samples are submitting to two low tides and two high tides. The drying and wetting time could be estimated about to 6 hours knowing that samples are covered and/or uncovered by the sea in a lapse of half an hour at every tide.

The salt level of the sea in La Rochelle is about 33,5 g/l and 36,7 g/l with a main part of sodium chloride (NaCl) and, in a lower part, magnesium chloride (MgCl<sub>2</sub>), calcium chloride (CaCl<sub>2</sub>), magnesium sulphate (MgSO<sub>4</sub>), calcium sulphate (CaSO<sub>4</sub>) and potassium hydrocarbonate (KHCO<sub>3</sub>).

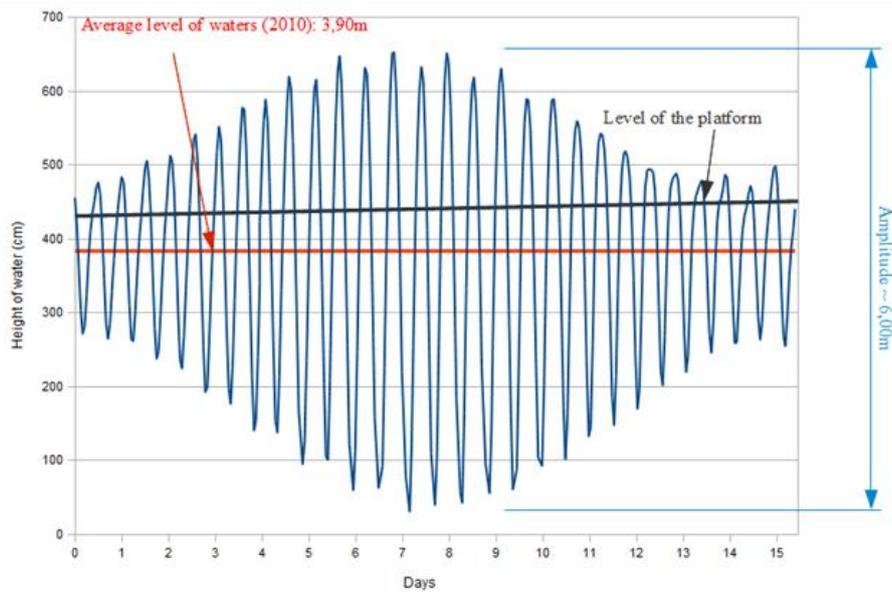


Fig.2. Evolution of the height of water on 15 days duration

## 2.2 Characterization of concrete

Since many years, this platform is used to study the behaviour of cementitious materials exposed in environmental aggressive conditions. The objective was to study the effect of nature and the amount of cement used on the degradation. It was observed that all mortars were degraded but these degradations depend on the materials used. In fact, first conclusions showed that mortars composed with high cement content and mortars made with Pouzzolanic cement were more resistant to environmental aggressions (Guillon, 2004).

It was understood later that this phenomenon was mainly due to the interaction between the cement matrix and the salt contained in the sea, by chemical processes of dissolution-precipitation and physical processes involving molecular absorptions.

Since then, other studies have been carried out, particularly one study about high performance concretes (French national project BHP 2000,) For this project T samples (figure 1) have been put down on the tidal zone to quantify the durability gain of the high performance concretes. These concretes by their particularities (high performance), showed very good characteristics regarding chlorides ions penetration.

During the last years, LEPTIAB (La Rochelle University) kept working on this research theme by focusing particularly on the means of characterization for cementitious materials degradation. So, experimental techniques were developed to follow-up the evolution of corrosion in steel concrete and also to estimate the time to corrosion initiation. This work was carried out in the framework of PhD of Tahlaiti (Tahlaiti, 2010) linked to the European project MEDACHS (Marine Environment Damage to Atlantic Coastal Historical Structures, 2005-2007).

In the laboratory, the follow-up of corrosion is carried out by using two electrochemical techniques.

The first method is the measurement of potential corrosion between the reinforcement and reference electrode (figure 3, Table 1) (Gonzalès et al., 2004) (ASTM C876-91, 1991).

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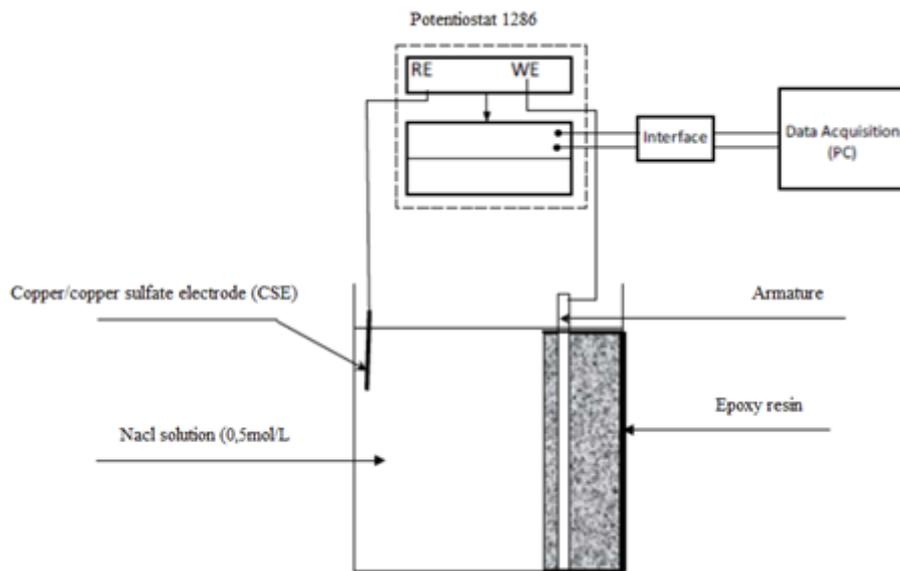


Fig.3. Schematic representation of Open circuit potential (OCP) measurement

Table 1. Corrosion condition related with half-cell potential measurements (ASTM 87-91, 1991)

Open circuit potential (OCP) values (V vs. CSE)	Corrosion condition
>-0,2	Low risk of corrosion
-0,35 to -0,2	Intermediate corrosion risk
<-0,35	High risk of corrosion

This method is simple and fast but gives only a qualitative estimation of the state of the electrochemical reinforcement (table 3) and the results depend on the quality of the experimental device. Therefore, it is suitable to link the potential corrosion measurements with another experimental investigation: the electrochemical impedance spectroscopy (EIS).

This method was developed in the laboratory during Poupard PhD thesis (Poupard, 2001) (Aït-Mokhtar et al., 2006), then optimized during Tahlaiti PhD thesis (Tahlaiti, 2010). This method is less developed than the first one but it is more precise in the following-up of corrosion in reinforcements (figure 4).

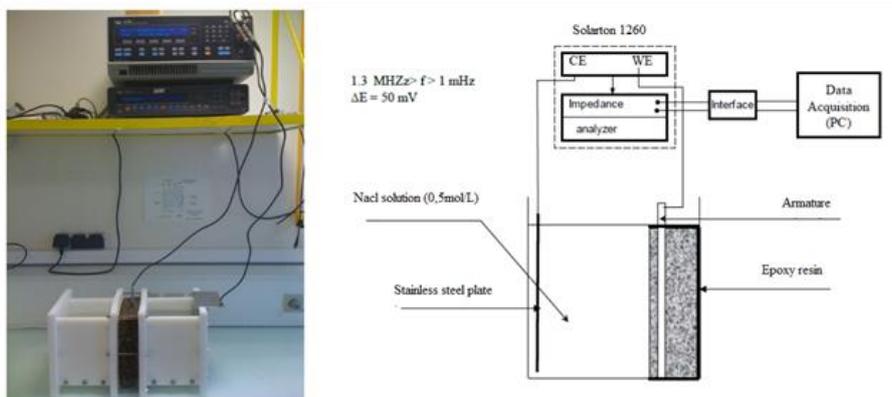
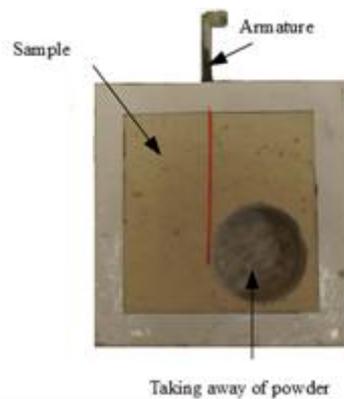


Fig. 4. Photography and schematic representation of E.I.S. measurements

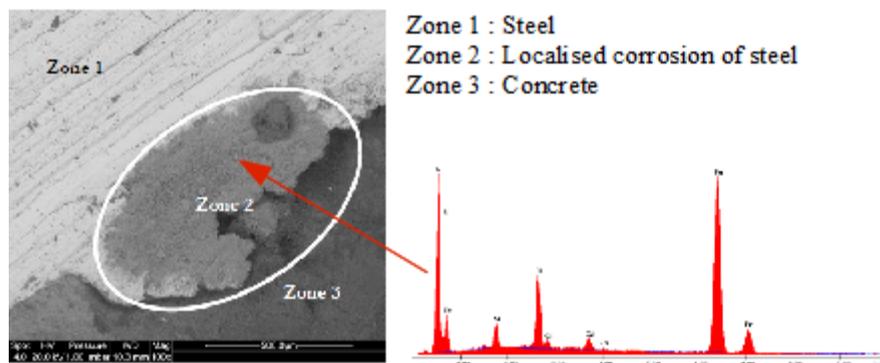
In fact, this second experimental technique gives the possibility to estimate a steady-state corrosion rate and the time necessary to corrosion initiation of reinforcements with much accuracy and stable measurements. To complete the time of corrosion initiation, a chloride profile is measured in the cover concrete with a particular determination of the critical chloride concentration at the concrete-reinforcement interface.

The dimensions of samples used are  $40 \times 40 \times 3,5 \text{ cm}^3$  with surface of  $15 \times 15 \text{ cm}^2$  exposed to chlorides (figure 5). The other faces are covered by resin and the naked part of the reinforcement is protected by galvanization.



*Fig.5. Sample for corrosion initiation tests*

Finally, investigations are completed by using descriptions by morphological techniques (SEM Scanning Electron Microscopy and EDXA Energy Dispersive X-ray Analysis) to identify the nature and form of corrosions products. The figure 6 is an illustration of SEM analysis coupled by EDXA analysis.



*Fig.6. SEM image and EDS spectrum of a corroded zone*

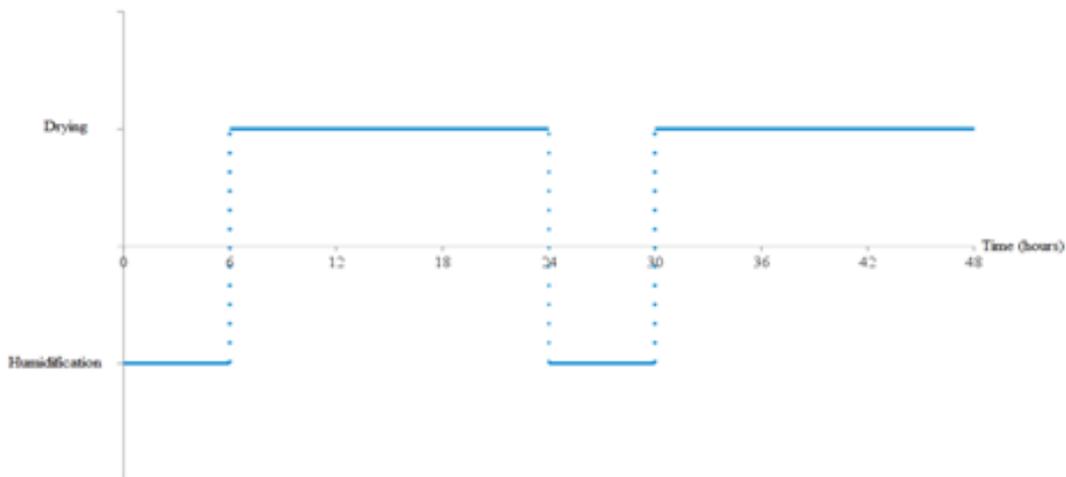
The results have proved useful and effectiveness of these techniques but the slowness of chlorides penetration during our work led us to research a possibility to increase the diffusion kinetics of chlorides ions. For this purpose, Tahlaiti (Tahlaiti, 2010) developed an automatically tidal simulator with cycles of drying - humidification and the exposures conditions controlled (temperature, chloride concentration,...). This simulator is composed of two large plastic compartments with a capacity of 600 L for each one (figure 7). The compartments are connected by a pumps system allowing ensuring drying-humidification. Ventilators were added on one of the two compartments to accelerate evaporation in the

## PERFORMANCE EVALUATION OF REPAIR SYSTEMS

drying period. The cycles of drying-humidification in the tidal simulator are different from those of tidal zone. They aim accelerating the processes of diffusion-convection. According to the literature (Hong, 1999), and after many preliminary adjustments in our laboratory, it was found that, the samples lose a maximum of water during the first eighteen hours of drying and absorb a maximum during the first six hours of humidification. For this reason, cycles with 18 hours for drying and 6 hours for the humidification were chosen.

The other procedure employed to accelerate the chlorides diffusion consists in linking the electrochemical measurements (electrochemical impedance spectroscopy EIS) with an electro-diffusion test. For this solution, another compartment was added to the cell (figures 4 and 8) in order to apply an electrical field across the sample. Therefore, during all the test duration, the chlorides migration by electro-diffusion and the electrochemical measurements are carried out alternatively until corrosion initiation.

However, the environmental conditions of materials exposed in the tidal zone or in the tidal simulator are not appropriated with the methodology of our tests because samples must be saturated before the beginning of measurements. This state is completely different from the reality of samples exposition. The interest of using this technique is that it allows us expanding our database in order to predict the behaviour of the studied materials due to corrosion induced by chlorides penetration.



*Fig.7. Tidal simulator and drying-humidification cycles*

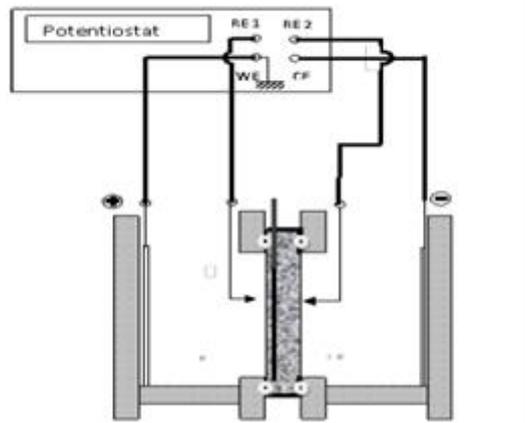


Fig.8. Schematic representation of electro-diffusion test

This test was performed using electro-diffusion cell by applying a constant electrical field between the two opposite sides of the sample. Downstream compartment contains basic solution and upstream compartment, aggressive solution based on basic solution. The amount of chloride ions, which crosses the specimen, is determined by potentiometric titration. The effective diffusion coefficient of chloride ( $D_{eff}$ ) is calculated according to NERNST-PLANCK equation.

Usually, all of analysed materials are prior characterized by standard tests to determinate their durability indicators. Therefore, chloride diffusion coefficient, water and mercury porosimetry, capillary absorption coefficient and gas permeability are determined systematically.

With these durability indicators, it is possible to estimate with predictive models, the exposure time necessary to reach a critical chloride concentration at the reinforcement. To set up the predictive tools, multi-species models of ionic diffusion in unsaturated cementitious materials (corresponding to exposition to wetting-drying cycles (tidal zone), based on the Nernst-Planck equation) are used. The results of numerical simulations are compared to those of the experimental results (samples in tidal simulator and tidal zone).

In summary, the figure 9 presents the followed stages to characterize materials exposed to wetting-drying cycles.



Fig.9. Experimental and numerical modelling methodologies

Results presented in Table 2 are a summary of some work carried out by Tahlaiti (2010). This work focused on the durability of reinforced concretes in unsaturated environment. Ordinary reinforced concretes (C15 and C30) have been exposed in tidal zone and tidal simulator. The concretes were made with cement CEM II B/LL 32.5 and quarry aggregates.

*Results show that the chloride ingress is more accelerated in laboratory simulator than in tidal zone. This is mainly due to duration of drying period (18 hours in laboratory, 6 hours in tidal zone).*

Table 2. Experimental results of concrete (C15 and C30) (Tahlaiti, 2010)

		C15	C30
Water porosity		15% +/- 0.51	12% +/- 0.83
Gas permeability (m <sup>2</sup> )		8*10 <sup>17</sup>	9*10 <sup>18</sup>
Effective chloride diffusion coefficient De <sub>Cl-sat</sub> (10 <sup>-12</sup> m <sup>2</sup> /s)		8.91	1
Tidal simulator	Initiation corrosion time (days)	250-280	400-470
	Total critical chloride concentration (% by weight of cement)	0.21	0.16
	Free critical chloride concentration (% by weight of cement)	0.11	0.1
Tidal zone	Initiation corrosion time (days)	270-340	470-520
	Total critical chloride concentration (% by weight of cement)	0.2	0.33
	Free critical chlorides concentration (% by weight of cement)	0.15	0.25

### 2.3 Characterization of commercial available repair materials

Actually, research tasks continue specifically on the characterization of commercial available repair materials. The aim of this research is to evaluate the performances of these materials against the corrosion induced by chlorides diffusion. The tests, found in the literature, to check the suitability of repair materials aim, in general, to find out their mechanical characteristics and only in few cases, results on their durability characteristics, resistance against chloride penetration and characterization of these materials regarding the corrosion resistance can be found in the literature. For this work we use the same previously methodology (figure 9) on eight patching mortars. These materials were selected to represent the generic type of repair mortars that are presently used in the repair of deteriorated concrete. They are commercially available, pre-packed standardized patching mortars (standard EN 1504) ready to be mixed and classified into two groups: cement mortars and cement mortars modified by polymers.

For this study the preparation of the samples is more difficult, because we have to do reparation according to the European standard (EN 1504, 2005). The manufacturing of the samples was made such shown on the figure 10, via several stages:

- ✓ Stage1 : Manufacturing of silicon borrow
- ✓ Stage2 : Installation of borrows and reinforcement

- ✓ Stage3 : Casting of concrete
- ✓ Stage4 : Release borrows from the mould    Stage 5 :Casting of mortar
- ✓ Stage 6 : Release samples from the mould
- ✓ Stage 7 : Galvanization of reinforcement
- ✓ Stage 8 : Conservation in wet chamber

Tests were carried out in saturated environment.



Fig.10. Manufacturing procedure of repaired reinforced concrete samples

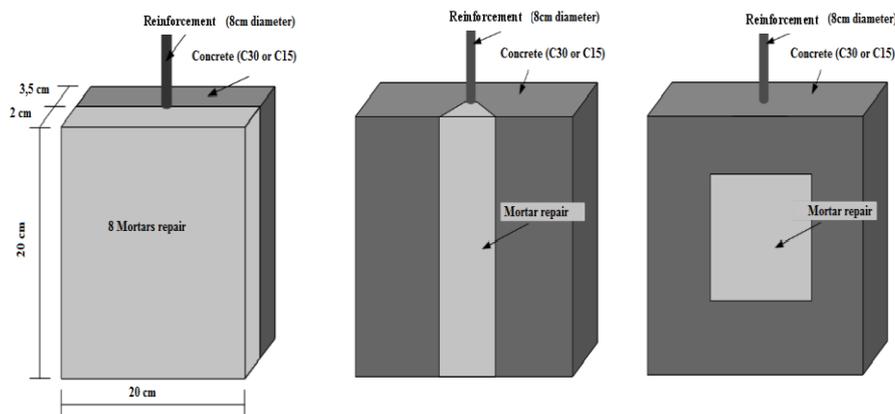


Fig.11. Reinforced concrete sample repaired with mortar

The first results of characterization (mortar and concrete support) are given in table 3:

Table 3. Durability indicators of concrete and mortars repair

	C15	C30	Mortars repair
Water porosity (%)	15,8	12,8	from 14,2 to 26,9
Gas permeability (m <sup>2</sup> ) (Drying temperature: 65°C , 15 days)	4*10 <sup>-16</sup>	5*10 <sup>-17</sup>	from 7,69*10 <sup>-19</sup> à 4,65*10 <sup>-17</sup>
Effective chloride diffusion coefficient DeCl-sat (m <sup>2</sup> /s)	7,89*10 <sup>-12</sup>	-	from 2,20*10 <sup>-13</sup> à 3,36*10 <sup>-12</sup>

According to the table 3, we remark that the mortars repair improve the resistance of concrete against the chloride penetration.

### 3 Study of repair materials in Saint Nazaire site

To evaluate durability performance an exhaustive experimental study was done on different repaired method with materials which are easy available with French furnishers. One of these was used for repairing the Wharf (Rosquoet et al, 2006) (see 3.1).

This research project was also done in the framework of a French national project called MAREO ("MAintenance et REparation des Ouvrages litoraux en béton" - [http://www.pole-geniecivil-ecoconstruction.fr/download\\_assets/12](http://www.pole-geniecivil-ecoconstruction.fr/download_assets/12)).

This study focus then on two different aspects:

- the durability of four coupled repair techniques/materials based on ready to mix concrete;
- the comparison of carbon (FeE500) and stainless steel (grade I.4362) performance associated with the previous repairing methods.

The four coupled repair techniques/materials based on ready to mix concrete tested and characterized are:

- Dry shotcrete (aggregates size 0-8 mm);
- Wet shotcrete (aggregates size 0-2 mm);
- Mortar implemented manually with the same material than the latter one (aggregates size 0-2 mm);
- Formed concrete (aggregates size 0-10 mm).

This experimental work is structured around tests on structures (beams in natural area) and laboratory tests. When the beams were repaired with the studied method/material, slabs were also cast for laboratory tests: some to determine indicator durability for these materials and some to evaluate durability performance with accelerated tests. (Perrin et al. 2010)

#### 3.1 Characterization of the specimens

Tests on structures are realised on 4 beam specimens, originated from a demolition site in northwest France. The initial material is characterized with classical techniques: determination of gas permeability and of chloride migration coefficient (table 4). Values obtained for these two parameters are in a good range as the beams are 80 years old: the concrete is not so damaged and contaminated. The indicator used to evaluate the damage state of these specimens is the chloride profile (figure 12). Chloride profiles are realized after the extraction of ions using the procedure described by AFREM (AFPC/AFREM, 1997) and GRANDUBE (Arliquie et al, 2007). The mass concentration in chlorides is compared to the threshold value noticed in the NF EN 206-1 standard (NF EN 206-1) of 0,4% of the cement mass (i.e. 0,065% of the concrete mass if the latter is supposed to be dosed at 375 kg/m<sup>3</sup> of cement).

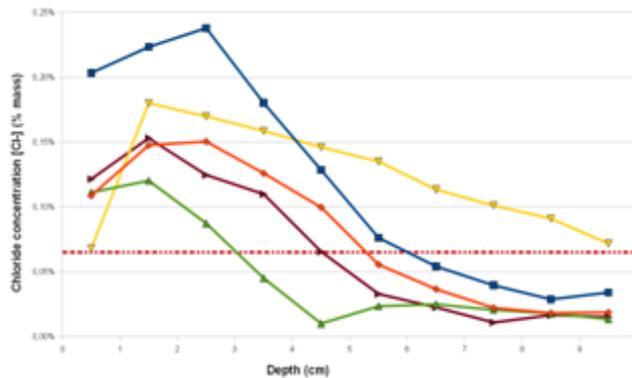


Fig.12. Chloride profiles for unrepaired beams (each curve concerns a different beam)

Table 6. Characteristics of unrepaired beams concrete

Parameters	Values
Intrinsic permeability ( $m^2$ )	$10^{-16}$ - $10^{-17}$
Migration coefficient (permanent flow, $m^2 \cdot s^{-1}$ )	$9.3 \cdot 10^{-10}$ - $4.3 \cdot 10^{-9}$

Concerning the beam specimens, the maximum concrete depth infected by chlorides is 6 cm. The infected concrete is then detached from beams on a 6 cm layer by a hydrodemolition method. The four repair techniques are used on the four different beams. Repaired beams are aged in tidal area at IFREMER laboratory (Institut Français de Recherche pour l'exploitation de la Mer-French Research Institute for Exploitation of the sea) following a natural tide cycle of 12 hours (6 hours drying and 6 hours wetting). This French research institute is located in Brest on the Atlantic coast (2.5 hours north from Saint-Nazaire). Repairs durability is appreciated at different time by proceeding to the realisation of chloride profiles on samples coming from beams and by making some non-destructive measurements which are done by IFSTTAR (Benmeddour et al, 2011, 2012).



Figure 13 .Beams repaired in natural site

### 3.2 Characterization of exposed repair samples

Slabs of 50 cm x 50 cm x 25 cm have been realised with the four repair techniques. The specimens have been extracted by coring into slabs to allow a characterization of these four materials. The indicators selected for this characterization stage are all subjected to a standard test (figure 14 a-d) (Arliguie et al, 2007) (NF EN 13412). The set of measurements are made on several samples to supply the data base concerning heterogeneity of repair materials as well as the estimation of measurement uncertainty.

Table 7 presents results obtained concerning the characterization of the repair materials chosen in this study (Perrin et al, 2010).

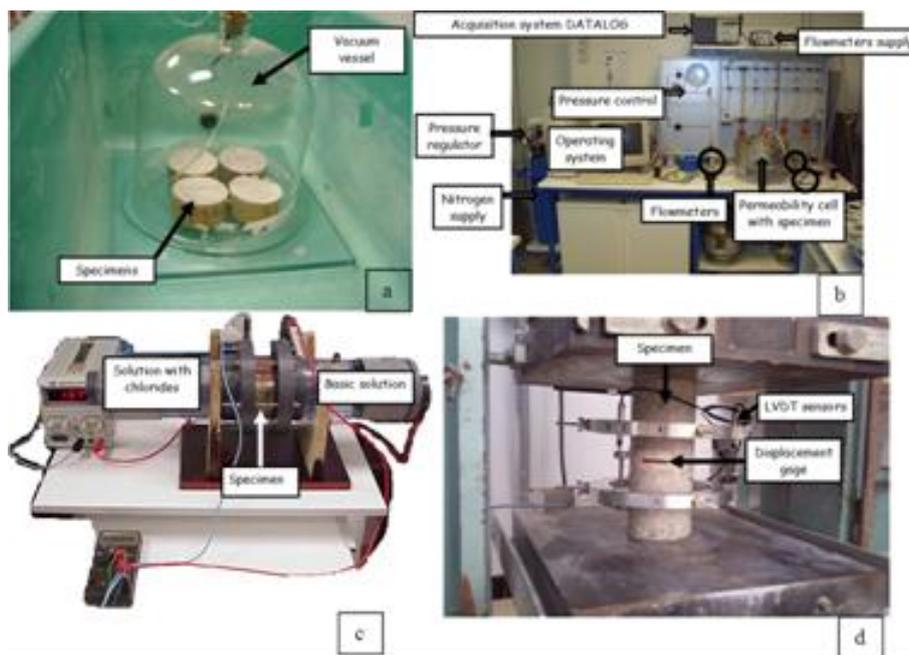


Fig. 14. Experimental set-up, a) porosity device, b) permeability device, c) chlorides migration device, d) mechanical set-up

Table 7. Characteristics of repair materials

Materials / techniques	Porosity (%) (3 tests)		Permeability (m <sup>2</sup> ) (3 tests)		Compressive strength (MPa) (3 tests)		Young modulus (MPa) (2 tests)		Poisson coefficient (1 test)
	Mean	Standard deviation	Mean x 10 <sup>17</sup>	Standard deviation x 10 <sup>17</sup>	Mean	Standard deviation	Mean	Standard deviation	
Dry shotcrete	12.6	0.26	2.09	1.53	49.27	0.57	31800	1140	0.22
Wet shotcrete	20.3	0.55	15.6	7.4	54.36	0.54	32500		0.27
Mortar implemented manually	22.4	1.05	17.0	5.14	50.00	1.06	23000	75	0.22
Formed concrete	16.6	0.78	1.25	0.05	67.07	0.32	34300	200	0.25

Results obtained for porosity tests show a general trend (table 8). Materials for formed concrete and dry shotcrete have porosity significantly lower than the material for wet shotcrete and the mortar implemented manually. We can suppose that the same material used for these two construction techniques is a more porous one than the two others due to its lower size of aggregates. We can also note that the materials implementation influences the porosity values. Indeed, the manual method exhibits a slightly porosity than wet shotcrete.

The porosities of wet shotcrete and of the mortar implemented manually are relatively high.

Permeability values are relatively dispersed (table 8) for dry shotcrete due to the heterogeneity of the material. If we compare values of porosity and permeability to the AFGC (Association Française de Génie Civil-French Civil Engineering Association) guide (AFGC,2004) (table 5), porosity values show low potential durability for materials while permeability values are typical of mean or high potential durability.

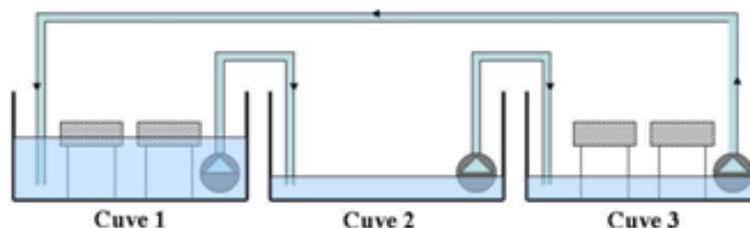
Concerning the mechanical characteristics, they seem close of values announced by manufacturers except for the formed concrete which shows values far exceeding guaranteed values.

*Table 8. Comparison of permeability and porosity values according to the AFGC guide (AFGC,2004)*

Materials/techniques	Permeability (m <sup>2</sup> ) (2 bars)	Potential durability	Porosity (%)	Potential durability
Dry shotcrete	24.10 <sup>-18</sup>	High	12-14	Mean
Wet shotcrete	260.10 <sup>-18</sup>	Mean	>16	Very low
Mortar implemented manually	290.10 <sup>-18</sup>	Mean	>16	Very low
Formed concrete	73. 10 <sup>-18</sup>	High	>16	Very low

### 3.3 Accelerated tests in laboratory

The second kind of material tests concerns slabs of 45x45x12 cm<sup>3</sup> made also with the same four repair materials. Some slabs are prepared with carbon steel rebars as well as stainless steel rebars. An accelerated ageing of slabs is realised in tidal-range conditions, with immersion-drying cycles, at CERIB laboratory (Centre d'Etudes et de Recherches de l'Industrie du Béton-Research and Development Institute of Concrete Industry). To accelerate the ageing, cycles of 6 hours of immersion and 18 hours of drying are chosen. The drying is accelerated with a ventilation system near the upper side of slabs (figure 15 and 16). To accelerate more the penetration of chlorides, slabs are only partially immersed. The saline solution used is composed by 35 g/L of salt so nearly 20 g/L of chlorides. A waterproof resin is applied on the lateral sides of slabs in order to simulate a propagation of the chloride front in a single direction.



*Fig.15. Wetting/drying cycles in CERIB*



*Fig. 16. Wetting/drying cycles in GeM*

The durability indicator chosen for these tidal range tests is the depth of chloride ions penetration. Some samples are tested at different times to compare the evolution of the chloride ions penetration in the different materials. These tests should enable the determination of the kinetics of chloride ions diffusion within material used. Chloride profiles are realized after the extraction of ions using the procedure described by AFREM (AFPC-AFREM, 1997).

The monitoring of chlorides penetration inside the different materials aims to correlate initial parameters (porosity, permeability, mechanical characteristics) to the materials capacity to prevent durably the chlorides to reach metallic rebars.

Tests on specimens cored in slabs in tidal area at CERIB laboratory has been made after 43 cycles of tide (43 days). The collected free and total chloride profiles are presented in the figure 6. The free chlorides are lower than the total chlorides for low depth but after 8 mm the values are similar (excepted for the formed concrete) because it needs time for chloride to be bound.

The standard NF EN 206-1 (NF EN 206-1) provides a chlorides content limit of 0,4% (compared to the cement ratio) to begin rebars corrosion. The chlorides content limit reported to the concrete mass is then of 0,064% (supposing that the cement dosage is of 350 kg/m<sup>3</sup>). If we apply this value to the different chlorides profiles, we can determine the penetration depth corresponding to this threshold (table 8). If we compare the behaviour of materials towards chloride ions penetration (figure 17), we can observe that near the tidal surface, the material having the most important ion content is the dry shotcrete. We can also notice that dry shotcrete, wet shotcrete and mortar implemented manually have relatively close critical depths (<10mm). Therefore, the formed concrete reaches the chlorides threshold for more important depths (13 to 18 mm) though maximal contents are not the highest. Maybe the cast material contains already chlorides before the accelerated tidal test. This questioning will be investigated by analysing some ready to mix concrete.

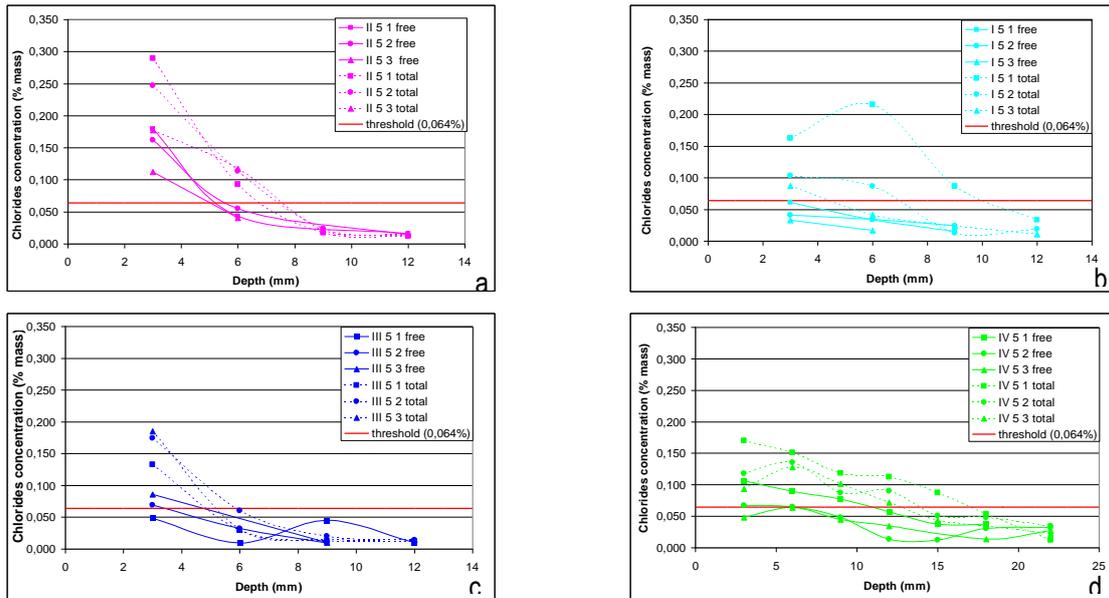


Fig.17. Chlorides profiles in slab submitted to accelerated test: a) dry shotcrete, b) wet shotcrete, c) mortar implemented manually, d) formed concrete

As unexpected, the highest critical depth is obtained for the formed concrete which has a good porosity and the highest compressive strength.

Table 9. Critical depth of chlorides

Materials/techniques	Threshold depth
Dry shotcrete	7 to 8 mm
Wet shotcrete	4 to 10 mm
Mortar implemented manually	5 to 6 mm
Formed concrete	13 to 18 mm

Some NDT methods (acoustic emission by IFSTTAR, electrochemical measurements by GeM) are also used in order to evaluate the potential of these methods towards corrosion estimation. The kinetic of rebars corrosion can be relied to the chloride ions diffusion due to an electrochemical monitoring. Besides, the benefit of using stainless steel rebars instead of classical ones is evaluated in terms of durability. To complete results, some small repair concrete reinforced slabs of 16x16x 4 cm<sup>3</sup> with a real-time mechanical (displacement gauges) and electrochemical monitoring are developed and placed in accelerated tidal conditions (figure 18). Results are not available by now.

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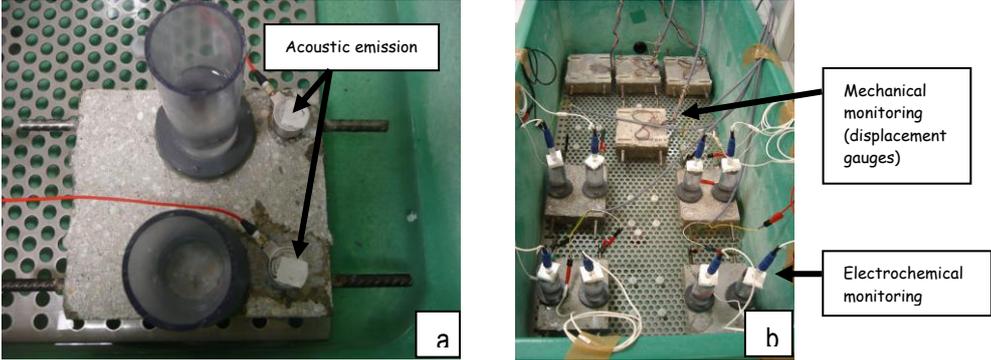


Fig.18 - Experimental set-up for small slabs monitoring, a) acoustic emission monitoring, b) electrochemical and mechanical monitoring.

## 4 Conclusions

In this report the behaviour of small samples of concrete exposed to chloride ingress in two experimental sites, is described. The results highlighted that the composition of concrete affect considerably the chloride transport. The mains results obtained are:

In La Rochelle site, the two concretes exposed to the tidal zone were manufactured with the same cement (CEMI) but have a different porosity 15% and 12% respectively. The critical chloride concentration (by weight of cement) obtained are 0.2 and 0.33 respectively. Nowadays, repair mortars are being tested.

In Saint Nazaire site, 3 repair materials are tested. The dry shotcrete have porosity significantly lower than the material for wet shotcrete and the mortar implemented manually. In the same way, the dry shotcrete seems to be more resistant to chloride ingress than the other repair materials studied.

## 5 References

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