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Reinforced Concretes of Tomorrow: Corrosion Behaviour according to Exposure Classes

V. Bouteiller[1], E. Marie-Victoire[2,3], A. Bonnet[1], V. Da-Silva[1], L. Adelaïde[1], J. Saint-Ange Billo[1], C. Da-Costa[1], M. Bouichou[2,3], J. Ducasse-Lapeyrusse[2,3], J. Mai-Nhu[4], P. Barthélémy[4], P. Turcry[5], F. Cussigh[6], S. Chanut[7]

[1]Univ Gustave Eiffel, MAST-EMGCU, F-77454 Marne - la- Vallée, France,
veronique.bouteiller@univ-eiffel.fr, amandine.bonnet@univ-eiffel.fr, victor.da-silva@univ-eiffel.fr,
lucas.adelaide@univ-eiffel.fr, saint-ange.billo@univ-eiffel.fr

[2]Centre de Recherche sur la Conservation (CRC), Muséum national d'Histoire naturelle, CNRS,
Ministère de la Culture. France

[3]Laboratoire de Recherche des Monuments Historiques (LRMH), Ministère de la Culture, 29 rue de
Paris, 77420 Champs-sur-Marne, France, elisabeth.marie-victoire@culture.gouv.fr,
myriam.bouichou@culture.gouv.fr, jean.ducasse-lapeyrusse@culture.gouv.fr

[4]CERIB, 1 rue des longs Réages - CS 10010 - 28233 Epernon cedex, France, j.mai-nhu@cerib.com,
p.barthelemy@cerib.com

[5]Laboratoire des Sciences de l'Ingénieur pour l'Environnement, (LaSIE), UMR 7356 CNRS, La
Rochelle Université, La Rochelle, France, philippe.turcry@univ-lr.fr

[6]Vinci Construction France, Nanterre, France, francois.cussigh@vinci-construction.fr

[7]Eiffage Infrastructures, France, sandrine.chanut@eiffage.com

Abstract. *Reinforced concrete is the most widely used building material but its durability in terms of concrete cover performance and corrosion of steel rebar is still a key point to be studied. To address this topic, within the frame of the national project PERFDUB, two series of eleven reinforced concrete specimens (with metric dimensions) were cast with innovative concrete mixes representative of the French experience, two shapes of rebar and two concrete covers. Then, these specimens were exposed in two natural exposure sites, one in Epernon for carbonation (XC4) and a second one in La Rochelle in the Atlantic Ocean in a tidal zone for chloride ions (XS3m). Their corrosion was carried out using non-destructive testing. In addition, in order to follow the corrosion evolution more accurately in a continuous way, two series of three specimens were casted with embedded sensors and were exposed in two other outdoor sites in Marne-la-Vallée (XC4) and in Eqiom facility (XS3e). The first results of this 20-year project in terms of corrosion of these reinforced concrete specimens obtained with laboratory and field equipment and with monitoring are presented in this paper.*

Keywords: *Concrete Mixes, Corrosion Behaviour, Corrosion Diagnosis, Monitoring, Exposure Classes, Carbonation Sit, Marine Tidal Site, Natural Ageing.*

1 Introduction

Reinforced concrete is the most widely used building material. Within the frame of the French national project PERDUB, an intensive series of studies mixing lab scale, natural ageing and durability modelling was launched in 2015 (IREX, 2023). In 2019 started a study dedicated to the evaluation of the performances of 11 (upon 42) of the concrete mixes designed against corrosion induced by natural carbonation or exposure to marine environment. The aim of this study was to tackle the key issue of durability which depends on the performance of the materials, concrete cover and corrosion resistance of the steel rebar, and on the exposure classes. This study based on reinforced concrete specimens of metric dimensions with two concrete covers, two rebar shapes and exposed to different natural ageing environments (carbonation, marine tide zone, marine atmospheric zone) is supposed to last for a period of 20 years in order to follow up contamination of the concrete cover, initiation and propagation phases of corrosion and finally concrete cracking. Corrosion evaluation was based on two approaches: Non Destructive Testing (with laboratory and on-site devices) performed once a year and continuous monitoring using embedded sensors.

In this paper, the experimental program and some preliminary results on corrosion evaluation depending on the exposure classes are presented.

2 Experimental Program

2.1 Specimens

Two series of 11 specimens were cast. The specimens were T-shaped, 0.16m-large, with two 1m² faces (1mx1m), and a foot (0.4x0.15m) to ensure their stability (Figure 2a and b). Two concrete covers were considered: 10mm and 20mm in order to evaluate the contamination of the concrete cover and the corrosion of the steel rebar. For each face of the specimen, two types of steel rebar were used: a smooth round shaped rebar (RL) representative of ancient constructions (and which surface can be determined accurately for electrochemical calculations) and one corrugated rebar (HA) representative of today's works. The 4 studied steels were not electrically connected. Eleven concrete mix designs (Table 1) with different binders, aggregates and water to binder ratios were selected upon the 42 mixes of the PN Perdub project (IREX, 2023). CEM I was chosen as usual cement and binders containing mineral additions such as fly ashes (V), limestone filler (L), slag (S), silica fumes (FS), siliceous addition (AS), or metakaolin (MK) were also considered. Different types of aggregates were used: two types of alluvial silico-limestones, one soft limestone and one hard limestone. Depending on the concrete mix design, water to binder ratios ranged from 0.35 to 0.6 (Table 1). More details can be found in (Marie-Victoire et al., 2022).

In addition, two series of 3 specimens with embedded sensors (Figure 2c) were cast choosing B01, B04 and B31 as concrete mixes. On those six specimens, a face contained 2 individual rebars with a concrete cover of 15mm and the other face contained a rebar network with a concrete cover of 30mm.

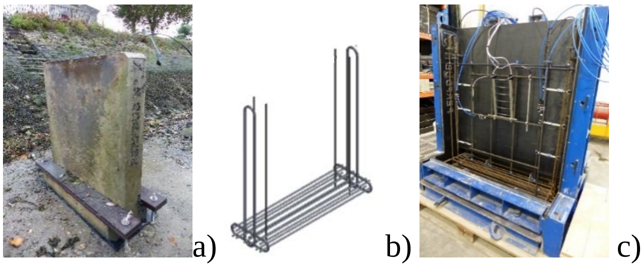

Figure 1. Reinforced concrete specimens (a), rebar arrangement (b), embedded sensors (c).

Table 1: Concrete mix designs, binders and aggregates.

Concrete mix designs	Binders			Aggregates	
	Binder (kg/m^3)	W/B	W/C	Type *	Water absorption (%)
B01	CEM I (289)	0.60	0.60	2	2.7
B02	CEM I (231) + Fly Ash (98)	0.54	0.77	2	2.7
B04	CEM III A (287)	0.61	0.61	2	2.7
B05	CEM I (122) + Slag (184)	0.57	1.44	2	2.7
B07	CEM I (267) + Limestone addition (188)	0.41	0.71	2	2.7
B31	CEM III A (383)	0.40	0.40	1	1.0
B36	CEM V (363)	0.46	0.46	4	4.0
B37	CEM V (374)	0.45	0.45	3	0.6
B38	CEM I (354) + Silica Fume (30)	0.35	0.38	1	1.0
B40	CEM I (261) + Siliceous addition (112)	0.47	0.67	2	2.7
B41	CEM I (302) + Metakaolin (76)	0.35	0.44	1	1.0

* *Aggregate types:* *1: Silica-limestone Alluvial, mixed rounded-crushed.*
2: Silica-limestone Alluvial, round + mixed.
3: Dense limestone, crushed.
4: Limestone, crushed.

2.2 Exposure Classes

The specimens were exposed in different natural sites and with therefore different exposure classes. For carbonation (XC4), the natural sites of Epernon (60km south-west from Paris - EP) was chosen for one series of 11 specimens (Figure 3a) and Marne-la-Vallée (20km east from Paris - MLV) for the three instrumented specimens (Figure 3b). For chlorides, two sites were selected on the Atlantic ocean shore : one in tidal zone in La Rochelle Harbor close to Saint-Nicolas tower (LR) for the second series of 11 specimens (XS3m) (Figure 3c) and one in the Equiom facility (EQ) for the other three instrumented specimens (XS3e) (Figure 3d).

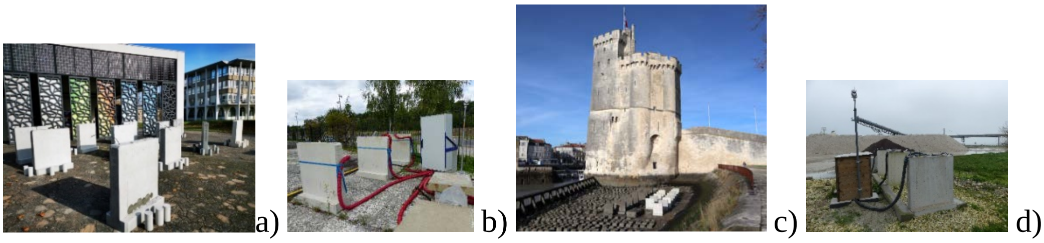

Figure 2. Different exposure classes – For carbonation: Epernon (a) and Marne-la-Vallée (b) and for chloride : tidal zone in La Rochelle (c) and sea shore in Eqiom facility (d).

2.3 Corrosion Assessment

Corrosion assessment was performed once a year on the 28 specimens using usual corrosion diagnosis based on instant Non Destructive Tests. The measurements were conducted using laboratory potentiostats (Parstat 2263 (Ametek) or PalmSens4 (HTDS)). Half-cell potential, linear polarisation resistance and impedance spectroscopy were used in order to calculate the corrosion current density. The electrochemical system was composed of three electrodes: the working electrode was the steel rebar, the reference electrode was a calomel electrode saturated with KCl (SCE, E(NHE) = +242 mV) and the counter electrode was a titanium/platinum-based grid. The electrical contact was provided by a wetted (tap water) sponge. Ecorr value (mV, SCE), was determined after a 10 min period which was long enough to obtain a stabilized signal. EIS measurements were performed using a 15 mV amplitude sine wave signal in the frequency range between 100 kHz and 0.19 Hz with seven points per decade. The Re value (Ohm) was determined at high frequency. For LPR measurements, a potential variation (±10 mV around the half-cell potential Ecorr using a sweep rate of 2.5 mV/min) was imposed and the current was recorded. The slope of the curve which is equal to (1/(Re + Rp)) was determined from the values obtained between 0 and +10 mV around Ecorr. The polarization resistance of the steel rebar, Rp (Ohm), was then calculated knowing the Re value. Finally, the corrosion current density Icorr ($\mu A/cm^2$) was calculated from the Stern and Geary equation : Icorr = B/Rp.S where B is a constant (considered as 26 mV (Andrade & Alonso, 2004)), Rp the polarization resistance (ohm) taking into account the ohmic drop and S the steel surface area of the rebar (3.1412x1x12=37.7 cm^2 in this study). Corrosion was analysed considering the four levels of corrosion suggested by the RILEM TC154 recommendation (Andrade & Alonso, 2004): negligible (< 0.1 $\mu A/cm^2$), low (0.1– 0.5 $\mu A/cm^2$), moderate (0.5–1 $\mu A/cm^2$) and high (>1 $\mu A/cm^2$). In addition, a continuous monitoring based on embedded sensors was carried out on the two series of three instrumented specimens. Multiple sensors embedded into concrete (Bouteiller et al., 2021; Raupach et al., 2013; Vennesland et al., 2007) allowed to monitor versus time: potential (ERE 20$^{®}$); resistivity and temperature (Multi Ring Electrodes$^{®}$); resistance, potential and current (Anode Ladder$^{®}$). In addition, temperature and relative humidity were measured in a dedicated reservation into the concrete (HMP110$^{®}$). Finally a weather station was installed at Marne-la-Vallée and at Eqiom facility. On each site, all the sensors were connected to a multiplexer, itself connected to an analyser, wired linked to a computer to provide data gathered in an automatic database as developed by Ibac$^{®}$ (Raupach, 2013). Measurements were performed every hour.

3 First Results and Discussions

3.1 Instant Corrosion Evaluation with NDT

Results from the 2021 measurement campaign, for the two series of 11 specimens exposed in the carbonation and the chloride sites, for the corrugated bar and for the 10mm concrete cover are presented in Figure 3. The values of resistance (Figure 3a), half-cell potential (Figure 3b) and corrosion current densities (Figure 3c) depended on the concrete mix and were in the range of 500 to 7 000 ohm, -500 to +100 mV and 0.1 to 4 µA/cm², respectively. For a chosen concrete mix, resistance, half-cell potential and corrosion current density values depended on the exposure sites (Andrade & Castillo, 2003; Bouteiller et al., 2012):

- The resistances were lower when the specimens were exposed to the chloride contamination than to carbonation (except for B38 but with a small difference);
- The half-cell potentials were more electronegative when the specimens were exposed to chloride pollution than to carbonation.
- The corrosion current densities considering the levels of the RILEM TC154 recommendation (Andrade & Alonso, 2004) were 1 to 2 orders of magnitude higher when the specimens were exposed to chloride contamination than to carbonation (except for B07).

These results can be explained by the fact that in the marine tidal zone concrete is wetter and even sea-water-saturated during high tides, with a total immersion of the specimens (and therefore the oxygen content is lower). In addition the wet and dry cycles due to the tides favors chloride ions penetration in the concrete cover, which reduces its resistance. All these factors lead to a higher corrosion rate. On the opposite, in the carbonated site, concrete is drier and therefore less corrosion activity is observed.

These preliminary results allow a classification of the steel rebar corrosion in the different concrete mixes exposed to different environments:

- The lowest corrosion of the steel rebar is observed for the concrete mixes B41, B38 and B31, probably because their water/binder ratio are the lowest (Table 1) and their resistance are the highest (Figure 4a).
- The most significant corrosion of the steel rebar is observed for the concrete mixes B04, B36, B07 and B40. These results are rather unexpected as the duration of exposure is about 1-2 years after casting. For the concrete mix B04 composed of a CEM III with low clinker content (Table 1), this can be explained by its lower water/binder ratio, and a potential carbonation during its exposure in XC4 environment in Epernon for about 1 year before being transferred to La Rochelle. More results on carbonation behaviour of the concrete mix designs of the PN PERFDUB project can be found in (Rozière et al., 2009).

The corrosion evaluation results obtained on the specimens in La Rochelle with transportable laboratory devices (this paper) are in good agreement with those obtained using on-site devices (Marie-Victoire et al., 2022). Finally this study highlights the need to introduce in the ongoing revision of the RILEM TC154 recommendations (Andrade & Alonso, 2004; Elsener, 2003; Polder, 2000) information on concrete mixes with binders different from Portland cement and particularly for lower carbon footprint cementitious materials.

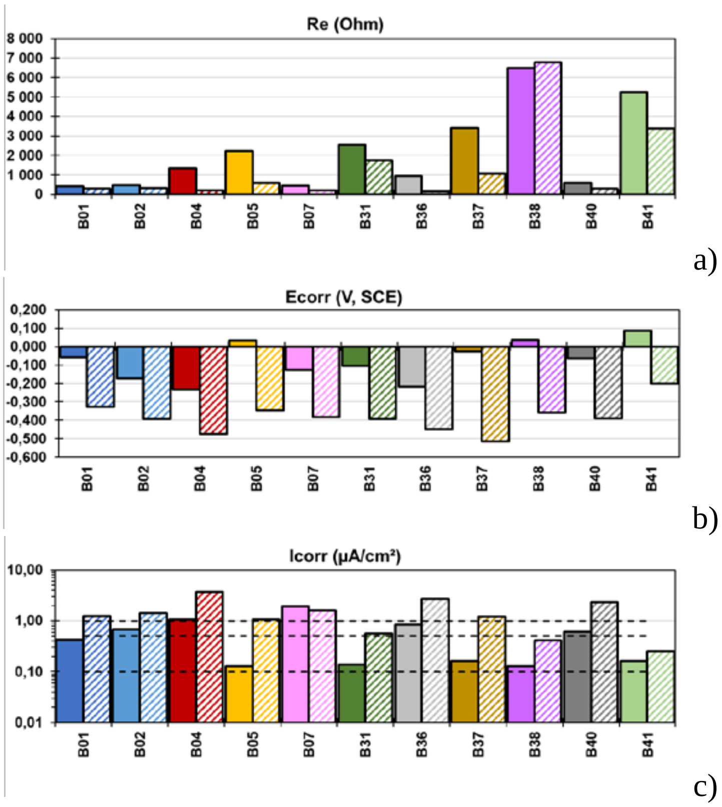

Figure 3: Comparison of resistance (a), half-cell potential (b) and corrosion current density (c) for the two series of 11 specimens depending on the exposure classes. The first histogram bar corresponds to the carbonation site (XC4) and the second histogram bar with the hatches corresponds to the chloride site (XS3m). The corrosion levels as indicated in Andrade et al. 2004 are represented with dotted lines.

3.2 Continuous Corrosion Monitoring

Instant corrosion current density cannot be used to predict accurately long-term corrosion because it is very dependent on climatic conditions as demonstrated in previous studies. Thus, a high corrosion current density after a rain event could under-estimate the durability of a reinforced concrete structure while a low corrosion current density after a sunny weather could over-estimate it (Bouteiller et al., 2016; Cremona et al., 2011). The evolution of the electrochemical characterizations with time is a key issue to (i) ascertain the different phases of corrosion (initiation, propagation, cracking) and (ii) accurately predict the durability on a long-term perspective. To address this topic, continuous corrosion monitoring based on embedded sensors into concrete and precisely located regarding the reinforcements in the specimens was attempted.

As an example of corrosion monitoring, Figure 5 presents the preliminary results of the Anode Ladder for resistance, voltage and current between reinforcement connection (30 mm concrete cover) and cathode (25 mm concrete cover) for the three instrumented specimens exposed in the carbonation site in Marne-La-Vallée (XC4) and in the chloride site La Rochelle-Eqiom (XS3m). From this graph, the influence of the exposure class was not significant during the first year. But clear differences between the three concrete mix B01, B04 and B31 was evidenced. Thus, the resistance of the concretes containing slag cement (B04 and B31) is higher than that of Portland cement-concrete (B01). It is also higher for B31 compared to B04 due to the variation in water/cement ratio which are respectively 0.4 and 0.6. Voltage and current did not indicate a corrosion activity of the rebar network with a 30mm concrete cover so far, but the monitoring is still on going.

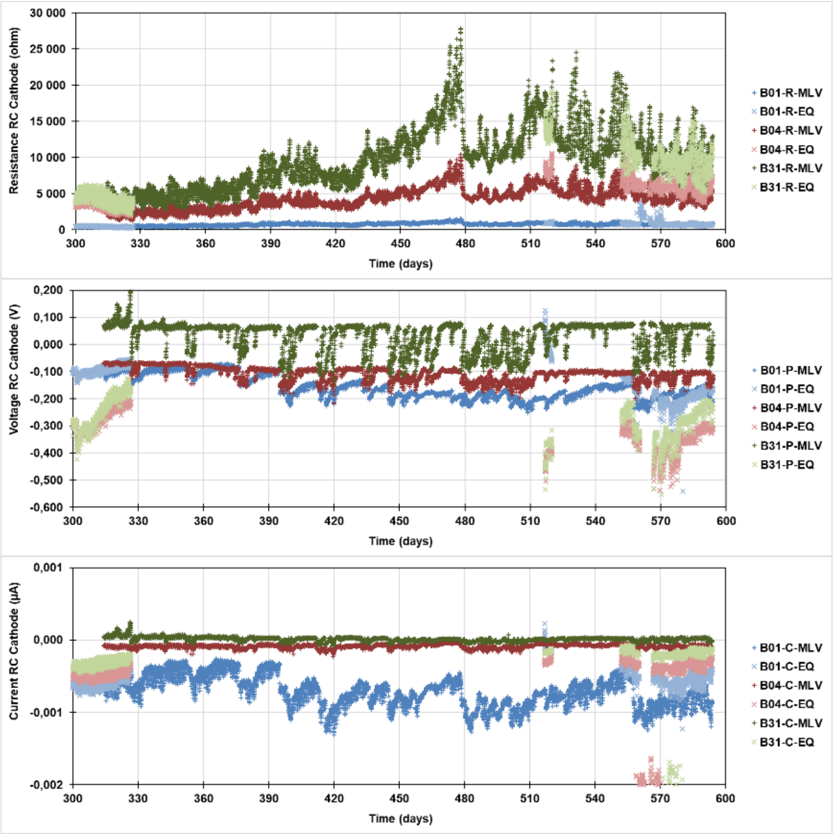

Figure 4: Resistance, voltage and current between reinforcement-connection and cathode (Anode Ladder sensor) for the instrumented specimens exposed at Marne-la-Vallée (darker color) and at Eqiom (lighter color).

4 Conclusions and Outlooks

A major study on the durability of reinforced concrete in terms of concrete cover performance and rebar corrosion (NDT and monitoring) has been initiated in 2019 as part of the French national project PERFDUB. From the preliminary results on corrosion of the steel rebar (corrugated reinforcement, concrete cover 10mm or 30mm and different exposure classes) presented in this paper, some conclusions can be drawn:

- Without surprise, the observed corrosion activity depends on the exposure classes and is higher in the marine site than in the carbonation site.
- Among the 11 concrete mixes studied, some reinforcements (with only 10 mm concrete cover) already show corrosion activity, which is rather unexpected given the two years study in natural ageing exposure sites.
- Non Destructive Testing and Monitoring results highlights different behaviours of rebar corrosion with regard to the concrete mix designs (Portland or slag cements).

Further studies are necessary to evaluate the influence of binders with low clinker content on rebar corrosion, with a specific attention paid to pH, carbonation depth, chloride ingress, oxygen content. Finally, these results will helpfully contribute to the integration of this new concrete mixes in the ongoing discussions within the frame of the new RILEM committee TC OCM (On-site corrosion condition assessment and prediction) and fib commissions.

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