

Concrete Durability towards corrosion risk – Protection strategy applied on the Rion-Antirion Bridge Project

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ABSTRACT: The long-term performance of concrete structures in a marine environment is controlled by the penetration of chlorides and the subsequent electromechanical corrosion of embedded steel. In Rion-Antirion Bridge Project, a lifetime of 120 years is required (ref.1). To achieve this requirement two strategies exist: (i) to postpone the penetration of chloride by relying on concrete quality and proper cover, or (ii) to use cathodic protection of reinforcement bars. For the Rion-Antirion Bridge, due to the size of the concrete structures, the former strategy (concrete durability approach) has been selected.

1 CONCRETE QUALITY & DURABILITY REQUIREMENTS

In order to achieve the long-term performance of 120 years of reinforced concrete structures of the bridge, it has been very important to properly characterise and evaluate the ability of the concrete to protect the embedded steel from corrosion.

Three major degradation risks on reinforced concrete are due to the chemical attack by seawater, the corrosion induced by chlorides and the corrosion induced by CO₂.

The strategy of the concrete durability approach to protect the steel relied mainly on a proper definition of the exposure zones, selection of appropriate concrete covers for each zone, and a proper characterisation and evaluation of concrete itself.

1.1 *Exposure Zones*

The structure had been split into several parts, which are:

- Pile Viaducts Foundations (bored or composite)
- Substructure externally exposed below MSL +10
divided in: - immersed zone below MSL -5
 - tidal & splash zone between MSL -5 & MSL +10
- Substructure externally exposed above MSL +10
- Substructure overland
- Bridge and Viaducts Superstructure

The most exposed zones in terms of corrosion risk are the structures externally exposed below MSL + 10. The immersed zone (below MSL -5.0) is much less critical than the splash and tidal zone (between MSL -5.0 and MSL +10.0), due to the lack of oxygen in this area.

1.2 Definition of covers

The different covers of the structure have been defined in accordance to the durability criteria selected. As a result, higher cover than contractually required has been selected (for the same exposure zone), especially in critical zones. Table 1 summarises the covers selected for the Rion-Antirion Bridge and applied throughout construction for the different exposure zones. A comparison with the contractual specifications shows that in the ‘immersed zone’ and ‘tidal and splash zone’ the cover has been increased by 20% and 13%, respectively.

1.3 Concrete specifications towards durability

In the same way, concrete specifications higher than those required by the TCC and the KME have been imposed in order to achieve the requirements of concrete durability.

Table 1 : Contractual Concrete specifications towards durability (as per KME and TCC) compared to Project specifications in relation to the exposure zones

Exposure Situation		Contractual Minimum Concrete Class	Minimum Concrete Class used	Contract Minimum Cover (mm)	Minimum Cover used (mm)	Contract Minimum W/C Ratio	Minimum W/C Ratio used	Contractual Minimum Cement content (kg/m ³)	Minimum Cement content used ² (kg/m ³)
Viaducts Pile Foundations		C25/30	C25/30	-	100	0.50	0.50	360	CEM II or CEM III 400
Immersed zone (below MSL -5)		C35/45	C45/55	50	60	0.40	0.40	400	CEM III 400
Tidal & Splash (MSL -5 to MSL +10m)		C35/45	C45/55	75	85	0.40	0.40	400	CEM III 420
Substructure externally exposed above MSL +10		C30/37	C45/55	50	50	0.45	0.40	360	CEM III 400
Substructure over land		C30/37	C30/37	45	50	0.45	0.45	360	CEM III or CEM II 400
Bridge & Viaduct Superstructure	Deck lower free surface	C30/37	C30/37 C60/75¹	40	40	0.45	0.45 0.40¹	360	CEM I & CEM III 400
	Deck upper surface	C30/37	C30/37 C60/75¹	30	30	0.45	0.45 0.40¹	360	CEM I & CEM III 400

Note 1: For cable-stayed bridge

Note 2: Where:

- Cem III is blast furnace slag cement Cem III/A 42.5 from TITAN with 60% to 64% of slag.
- Cem II is Cem II/B-M (W-P-LL) 32.5 N from TITAN.
- Cem I is Cem I 52.5 of TITAN.

Those specifications refer mainly on the choice of type of cement, the content of cement and the Water/Cement Ratio, according to the exposure situation of each part of the structure, with special specifications for marine environment. Table 1 gives the values of the different parameters as specified in the KME, and as finally used on site.

Based on experience gained, it is important to notice that the use of slag cement (CEM III) at a high quantity ($> 400 \text{ kg/m}^3$) combined with a low W/C ratio ($< 0,4$) in the most unfavourable zones is the most appropriate protection against corrosion risk.

2 VALIDATION OF CONCRETE SPECIFICATIONS AND SET UP OF REQUIREMENTS

Further to the previous definitions, the following strategy has been developed for the bridge project concrete control.

- 1) Specific tests related to durability of concrete have been defined and performed systematically at KG Laboratory for all mixes used in the project. Acceptance criteria have been chosen for those tests based on experience.
- 2) A simultaneous validation of the long-term performance of the critical areas concrete mixes has been undertaken by LERM laboratory.
- 3) Some additional tests on critical areas concrete mixes have been performed in KG laboratory to satisfy experts' requirements.

2.1 *General concrete requirements and results – All zones*

For all exposure zones, the main durability indicator has been selected to be the RCPT result (Rapid Chloride Penetration Test), combined with the WDP (Water Penetration Test) (Cf. ref.7)

Those two tests have been performed systematically on all Conformity Trials for each different mix defined for the structure.

Then the respect of the fresh concrete parameters within acceptable tolerances defined in Trial Mix Reports, guarantees results on hardened concrete (strength and durability characteristics) equivalent to the ones obtained during those conformity trials.

The acceptance criteria for those tests have been chosen so that:

- WDP $\leq 20\text{mm}$
- RCPT at 90 days $\leq 1000\text{C}$ in the splash zone
 - $\leq 2000\text{C}$ for substructures
 - $\leq 4000\text{C}$ for piles-foundations and Bridge & Viaduct superstructure (TQ 60465/0)

2.2 *Validation of long-term performance of concrete used in structures externally exposed below MSL +10 (Immersed and Splash & Tidal Zones)*

For this particular zone, the most exposed to corrosion risk, a most precise analysis has been performed to verify that concrete mixes complying with the previous requirements achieve adequate long-term performance. A complete study has been entrusted to LERM Laboratory (cf. Ref.9 and Ref. 10).

2.2.1 Measurements

Measurements of Oxygen Permeability (AFPC-AFREM method), as well as chloride diffusion coefficient (TANG LUPING's method) have been performed on cores taken on walls cast in site laboratory with concrete mixes aimed to be used on immersed and tidal and splash zones. The cores were taken and tested at different ages.

More particularly, measurements presented in 2nd LERM report (ref 10) have been performed on cores taken from walls cast with 425 formula of C45/55 (see following table 3), cured 3 days with water, and then installed in splash and tidal zone on site. The scope was to simulate concrete cast in situ (cone, pier shaft), and exposed in splash and tidal zone at a very early age (probably the worst situation).

2.2.2 Numerical Simulations

The results obtained at different ages on concrete blocks, combined with the chloride binding capacity of the cement paste have been used as input data in a finite element model using a general equation for the evolution of the diffusion coefficient with time (Cf. Ref10):

$$D = 1.10^{-12} t^{-\alpha}$$

with $\alpha=0,4297$.

This equation being determined with the help of the values measured, and the experience of LERM in similar projects as the Vasco de Gama Bridge in Portugal.

2.2.3 Interpretation

Those simulations lead to the presentation of chloride profiles in concrete at chosen dates, and at the requested 120 years.

On the same time, conservative and strict chloride threshold values (corrosion initiation) at reinforcement level has been defined based on experience and bibliography. The chloride threshold at the level of reinforcement (corrosion initiation) is about 0,4 % for immersion and airborne zones, whereas it is about 0,2 % in splash and tidal zones.

The superposition of the chloride profiles obtained with this threshold has allowed the validation of the long-term performance (120 years) of the Rion-Antirion Bridge Project concrete.

2.3 Other Tests

Taking into account Professor Gjorv advice on Durability Approach, some further tests have been performed on the mixes aimed to be used in immersed and splash zones, in order to reinforce the opinion of the experts on the long-term performance of this concrete.

The tests performed at KG laboratory are the following:

- Capillary and porosity tests (Cf. Ref 11)
- Resistivity measurements (use of RCPT test)

3 TEST RESULTS

3.1 Laboratory results

Laboratory results correspond to test results obtained during Trial Mixes in KG Laboratory, or at LERM premises. Anyhow, all cores and samples tested were coming from concrete cast for laboratory purposes at the Site Batching Plant under same conditions as during regular production.

3.1.1 RCPT and WDP Results

Table 2 summarises the RCPT and WDP Results of the principal mixes used on site:

Table 2 RCPT and WDP of all concrete mixes used on site

Class of Concrete	Use of Mix	Exposure Class	Cement (kg/m ³)	D Max (mm)	W/C Ratio	RCPT Results min-max (Coulombs)	WDP Result min-max (mm)
C45/55	Main bridge footing Antirion & Rion Viaduct Substructure in Splash zone	Substructure externally exposed below MSL +10 (immersed zone below MSL -5) and Splash Zone	Cem III 400	20	0,40-0,42	480-1040	2-10
C45/55	Cone & pier-shaft Pier Head In Situ Bored piles in Splash zone	Immersed zone below MSL -5 Splash & tidal zone (MSL -5 to MSL +10)	Cem III 420	20	0,39	220-600	0-1
C45/55	Mass Concrete in Dry Dock and In situ (Pier Head)	Immersed zone (below MSL -5) & Substructure exposed above MSL +10	Cem III 450	10	0,39	450-500	1-2
C50/60	Pylon Base	Substructure externally exposed above MSL +10	Cem III 420	20	0,37	200-360	1
C60/75	Pier shaft slab	Splash zone (MSL -5/MSL +10)	Cem III 490	20	0,33	220-390	5-10
C60/75	Pylon legs	Superstructure of Main Bridge	Cem III 327 Cem I 163	20	0,33	270-575	3-4
C60/75 Silica Fume 30 kg/m ³	Pylon legs	Superstructure of Main Bridge	Cem III 228 Cem I 228	20	0,37	530-710	-
C60/75	Deck on shore	Superstructure of Main Bridge	Cem III 490	20	0,33	320-370	5
C60/75	Deck off shore	Superstructure of Main Bridge	Cem I 450	20	0,33	1000-3500 at 30 days	-
C30/37 C35/45	Antirion & Rion Viaduct Substructure	Substructure overland	Cem III 400	20	0,44	700-1490	5-8
C30/37	Composite piles for viaducts	Viaduct piles foundations	Cem II 400	20	0,39	910-1380	8
C40/50	Antirion Viaduct prestressed beam & slabs	Bridge and Viaducts Superstructure	Cem III 140 - 150 Cem I 280 - 300	10	0,4	1420-2900	2-6
C25/30	Rion Viaduct bored piles	Viaduct Piles foundations	Cem III 400	20	0,5	1060-1420	20

It is important to notice that the results obtained are all complying with the previously defined requirements, and most particularly in the immersed and splash zone, those results are excellent, with RCPT values significantly lower than 1000 C.

3.1.2 LERM Study Results

a) Measurements

- The oxygen permeability has been measured to be $< 1.10^{-17} \text{ m}^2$ at 28 days
- The chloride diffusivity has been measured to be $< 1.10^{-12} \text{ m}^2/\text{s}$ at 28 days and $< 5.10^{-13} \text{ m}^2/\text{s}$ after 4 months.

Those results show already a good ability of concrete to prevent from chloride migration. On the same time, the chloride binding capacity of the cement paste has been evaluated (Cf. Ref9)

The results show that the capacity of chloride fixation by the binder is very high, approximately 50 % of the total chlorides present in the paste.

b) Numerical Simulations

Table 3 hereafter presents the evolution of the diffusion coefficient with time used in the simulations, with an extrapolation of the experimental results up to 100 years thanks to the evolution law presented in paragraph 4.2.1b).

Table 3 Chloride diffusion coefficient with time

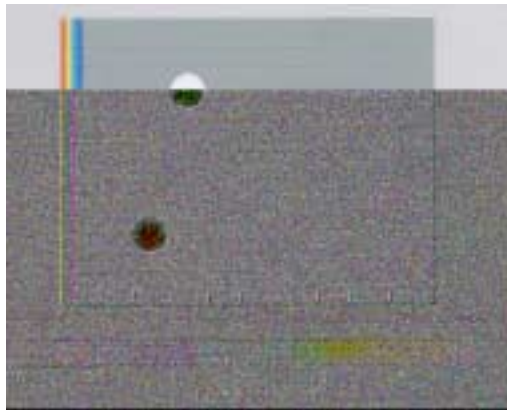
Time (month)	D (m ² /s)
0 - 1 month	5.10^{-12}
1	1.10^{-12*}
4	5.10^{-13*}
12	4.10^{-13*}
120	1.10^{-13}
1200	5.10^{-14}

*measured values

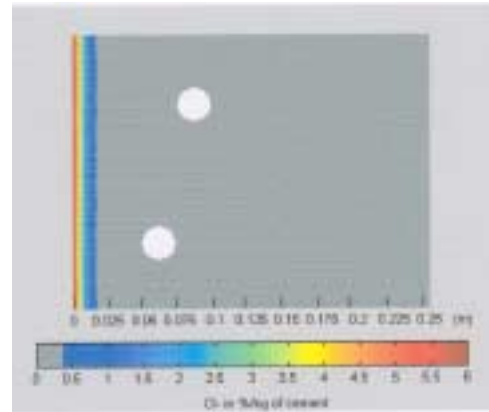
The results show an important decrease of the diffusion coefficient with time, which will lead to good long-term performance of the concrete.

c) Conclusions of the Study

These simulations gave the chloride profiles in concrete at 10 years and at 120 years in immersion and airborne zones, as well as in splash and tidal zones. They also show the relative position of the reinforcement bars according to the cover chosen. For those simulations, the value of the chloride diffusion coefficient $D = 1.10^{-13} \text{ m}^2/\text{s}$ at 10 years (see Table 3) has been used, although the decrease of this coefficient is less significant after 10 years. The value, therefore, taken for the calculations is conservative. Figure 1 and Figure 2 give the evolution of the chloride profiles with respect to the location of the external reinforcement (cover), taking into account the evolution of the diffusion coefficient with time.

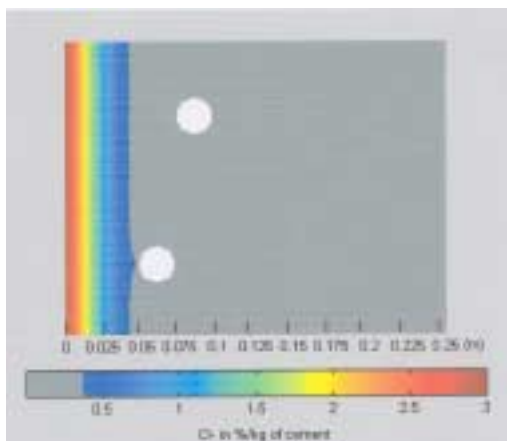


(a) Immersion and airborne zone

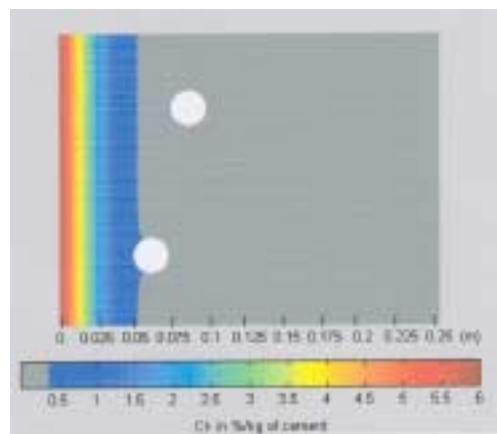


(b) Splash and tidal zone

Figure 1 Simulation of Chloride Profiles at 10 (ref. 10 LER00003/0)



(a) Immersion and airborne zone



(b) Splash and tidal zone

Figure 2 Simulation of Chloride Profiles at 10 and 120 years (ref. 10 LER00003/0)

The chloride profiles of Figure 2 indicate then that the diffusion coefficients determined for those concrete mixes comply with the durability requirement of 120 years with regard to the corrosion risk, provided that the value of the diffusion coefficient reaches a long-term (about 10 years) value of $D = 1.10^{-13} \text{ m}^2/\text{s}$.

In conclusion, the tests and the simulations performed by LERM confirmed that the required low level of diffusion coefficient can be obtained with the use of low W/C ratio combined with slag cement (for which compactness increases with time).

3.1.3 Other Tests

The main results on the capillary and porosity tests, as well as the resistivity measurements are presented in Table 4.

Table 4 Additional KG laboratory tests

Class of Concrete	Use of Mix	Exposure Class	Type of Cement	W/C Ratio	Resistivity min-max (Ohm.m)	Capillary Number K min-max (kg/m ² /s ^{-0.5})	Capillary Resistance Number M min-max (s/m ²)	Suction Porosity (%)
C45/55	Pier Base Rafts and Precast slabs	Substructure externally exposed below MSL +10 (immersed zone below MSL -5)	Cem III 400 kg/m ³	0,4	360 - 750	1.0 E 10 ⁻² 1.4 E 10 ⁻²	7.5 E 10 ⁶ 2.6 E 10 ⁷	9.3 13.0
C45/55	Rafts, Walls, Footing Top slab in Dry Dock Antirion & Rion Viaduct Substructure in Splash zone	Substructure externally exposed below MSL +10 (immersed zone below MSL -5) and Splash Zone (MSL -5 to MSL +10)	Cem III 400 kg/m ³	0,4	350 - 640	9.0 E 10 ⁻³ 1.3 E 10 ⁻²	1.2 E 10 ⁷ 2.0 E 10 ⁷	8.5 11.8
C45/55	Cone at Wet Dock Octogone In Situ Pier Head In Situ Rion Viaduct bored piles in Splash zone	Immersed zone below MSL -5 Splash & tidal zone (MSL -5 to MSL +10)	Cem III 420 kg/m ³	< 0,4	380 - 680	9.0 E 10 ⁻³ 1.2 E 10 ⁻²	8.0 E 10 ⁶ 1.7 E 10 ⁷	8.1 10.6
C45/55	Mass Concrete in Dry Dock and In situ (Pier Head)	Immersed zone (below MSL -5) & Substructure externally exposed above MSL +10	Cem III 450 kg/m ³	0,39	470 - 600	1.3 E 10 ⁻² 2.0 E 10 ⁻²	1.3 E 10 ⁷ 1.5 E 10 ⁷	11.2 12.5

3.2 Adequacy of Site Results

All the previous "laboratory" results show a very good ability of concrete to protect embedded steel from corrosion.

It is important at that point to notice that in Rion-Antirion Bridge Project, the extended quality control of concrete during production is the main guarantee of the compliance of the in-situ concrete with the laboratory concrete.

For this reason, during mix design and conformity trial mixes (Cf. Ref. 8) performed at batching plant, parameters of fresh concrete such as workability indicators (slump and flow) are fixed for each formula within narrow acceptable ranges. The achievement of hardened concrete characteristics and properties of in-situ concrete similar to those obtained during the trials are guaranteed by this way.

Those parameters are then systematically checked during concrete production at the batching plant, and concrete placement on site, and concrete is rejected if not complying with values fixed at mix design. (cf. Ref. 13)

Furthermore, during concrete production at the batching plant, concrete is first checked by the operators via the wattmeter (the acceptable ranges are also fixed at mix design for each formula). Then, the presence of the laboratory is necessary for any modification on the formula (ex. Water content), which guarantees once more good regularity of concrete produced.

Finally, concrete results obtained all along the production up to now show adequacy of the concrete produced for permanent works with the one performed for the laboratory.

On the other hand, good workmanship is well prepared and controlled under Works Methods Statements and Inspections and Tests Schedules defined precisely for each part of the structure the specific mix design, the curing process, the minimum cover, e.t.a.

Curing of concrete on site, for instance, is carefully followed up, especially in critical zones.

Nevertheless, in order to verify the adequacy of laboratory concrete with in-situ one, some coring has been punctually performed on selected by the Supervision Engineer part of structures of the Bridge (which appeared not to be perfectly made or cured) and the RCPT values have been checked. The results are presented in Table 5.

Table 5 Coring from actual production concrete pours

Mix No.	Structure Reference	Date of casting	Exposure Zone	RCPT Results on production samples	RCPT Laboratory results on the same formula
406	M4.40.RAFT8.2.2.	7/12/99	Immersed Zone (below MSL - 5.0)	697	480 - 1050
429	M3.40.RB1	11/04/00	Immersed Zone (below MSL - 5.0)	670-763-786	650 - 1040
	M3.40.WET26	16/03/00		733	
	M3.40.WET25	28/03/00		635-590	
446	M3.45. OC. 1-2	16/07/01	Splash Zone (between MSL - 5.0 and MSL +10.0)	351-390-341	450 - 500

Those results show a perfect compliance of the production concrete with the laboratory results.

Finally, it is also important to notice that cover is also carefully controlled on site before casting of structure parts, and also after formwork removal via a covermeter on random areas, and wherever difficulties or problems have been met before and/or during casting. From a design point of view two values of concrete cover are specified: the actual minimum value (value assumed in the design) and the nominal minimum cover (used during construction) which is 10 mm larger in order

to account for construction tolerances. This provides an additional level of security the minimum cover obtained during construction.

4 CONCLUSIONS AND SUBSEQUENT FOLLOW-UP

Concrete results obtained at laboratory and on site show a very good ability of Rion - Antirion Bridge concrete to protect the embedded steel from corrosion, and guarantee the achievement of a service life of 120 years.

It has been, however, decided to follow-up the concrete in-situ with testing similar to the one performed by LERM, in order to confirm its quality towards durability requirements directly, and hence obtain more results allowing the verification of service life assessment.

4.1 Validation of long-term performance of chloride diffusion coefficient

Additional cores have been taken in the walls cast for the initial durability study and installed in splash zone. They will be used by LERM in order to perform additional measures of Diffusion Coefficient, at later ages. Additional "real" points will be then added in the evolution curve and reinforce the assumption on the " α " value of the equation of evolution of the Diffusion coefficient, and hence on its long-term value.

4.2 Validation of uniformity of in-situ concrete quality compared to laboratory concrete

Non-destructive testing will be performed on the 4 piers in splash zone: several methods will be used to get precision in the results (radar, sclerometry, resistivity measurements). This will lead in the determination of low, medium and high compacity areas.

Then, a few cores (3 per zone) will be extracted from those areas and tested through a program similar to the one performed on laboratory samples in LERM. At least 3 zones (low, medium, and high compacity zones) will be selected in one pier, and 2 zones (low and medium compacity) on the others.

Additional cores shall also be taken to perform RCPT tests at KG laboratory.

4.3 Comparison of real chloride ingress and simulated values

During the construction phase, it is also proposed to cast reinforced concrete panels in-situ, similar in dimension to the ones cast for durability study in laboratory. Those panels will be cast during real pour of structural concrete with the same formula, and the same concrete staff, and kept under the same conditions as real structure. Those panels will allow performing measurements of the real chloride ingress at different ages, even after the construction period. Those ages will be proposed by LERM. Those concrete panels could also be used to obtain additional points in the evolution curve of Diffusion Coefficient, and reinforce again the equation proposed by the LERM. The exact program of testing shall be defined at a later stage, and be included in the Maintenance Manual of the Bridge.

5 REFERENCES

1. KME- Article 1.19
2. TCC- Volume 6
3. GKQ 30300/B: "Concrete Specifications"
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