RION ANTIRION BRIDGE PROJECT - CONCRETE DURABILITY TOWARDS CORROSION RISK

LE PONT DE RION-ANTIRION – LA DURABILITE DU BETON VIS-A-VIS DU RISQUE DE CORROSION

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ABSTRACT – The Rion-Antirion Bridge is a building site where the durability is a major factor in the definition of concrete mix design. In Rion-Antirion Bridge Project, a service lifetime of 120 years is required. Specific tests related to durability of concrete have been performed systematically at site laboratory for all mixes used in the project. Acceptance criteria have been chosen for those tests based on experience. Furthermore, an analysis of concrete durability including an assessment of expected service life has been carried out by LERM laboratory. The results of chloride penetration tests, 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. 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.

RÉSUMÉ – Le pont de Rion-Antirion est un chantier pour lequel la durabilité a été le facteur déterminant dans la mise au point des formulations. La durée de vie exigée par le cahier des charges est de 120 ans. Différents types d'essais ont été menés au laboratoire du chantier sur toutes les formules de bétons du projet. Les critères du cahier des charges ont été définis suivant les performances à long terme des structures en béton armé. En outre, une campagne d'étude de durabilité sur l'évaluation de la durée de vie de l'ouvrage a été menée avec le laboratoire LERM. Les résultats de résistance à la pénétration en chlorures obtenus sur des blocs en béton à différentes échéances, combinés avec la capacité de pénétration des chlorures du liant, ont été utilisés dans un modèle aux éléments finis utilisant une équation générale pour l'évolution du coefficient de diffusion en fonction du temps. Les résultats ont été concluants montrant une bonne capacité du béton à protéger les armatures de la corrosion et de garantir l'exigence de durée de vie de 120ans.

1. Introduction

The Rion-Antirion Bridge is the longest cable stayed bridge in the world with a continuous deck of 2,250 metres with over 1,000 metres of approach viaducts and further access roads.

It is located at the intersection of major roads in Greece which links the three most important cities of Greece and forms part of the European motorway network. The bridge is situated in an area of high seismic activity, with the two ends of the bridge founded on different tectonic plates, resulting in a relative movement of almost 2 cm per year.

The principal supports stand in up to 65 metres of water, and the main pier foundations measure 90 metres in diameter. The pier bases too were constructed on-site, before being floated into position in the Gulf, and lowered onto the seabed using water as ballast. The four main pylons were built in concrete using climbing shutters, and reach 164 metres above sea level. The three central spans measure 560 metres each and the two side spans, 286 metres.

In Rion-Antirion Bridge Project, a lifetime of 120 years is required. The long-term performance of concrete structures in a marine environment is controlled by the penetration of chlorides by relying on concrete quality and proper cover or the subsequent electromechanical corrosion of embedded steel. Thanks to concrete resistance against chloride ingress and due to the size of the concrete structures, the strategy of concrete durability approach has been selected.

2. Contractual 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 characterize and evaluate the ability of the concrete to protect the embedded steel from corrosion.

Three major degradation risks on reinforced concrete must be faced: the chemical attack by seawater, the corrosion induced by chlorides, the corrosion induced by CO_2.

The strategy chosen to protect the steel relied mainly on the following: a proper definition of exposure zones, the definition of appropriate concrete covers, and a proper characterization and evaluation of concrete itself.

2.1 Exposure zone

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 and 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.

2.2 Definition of covers

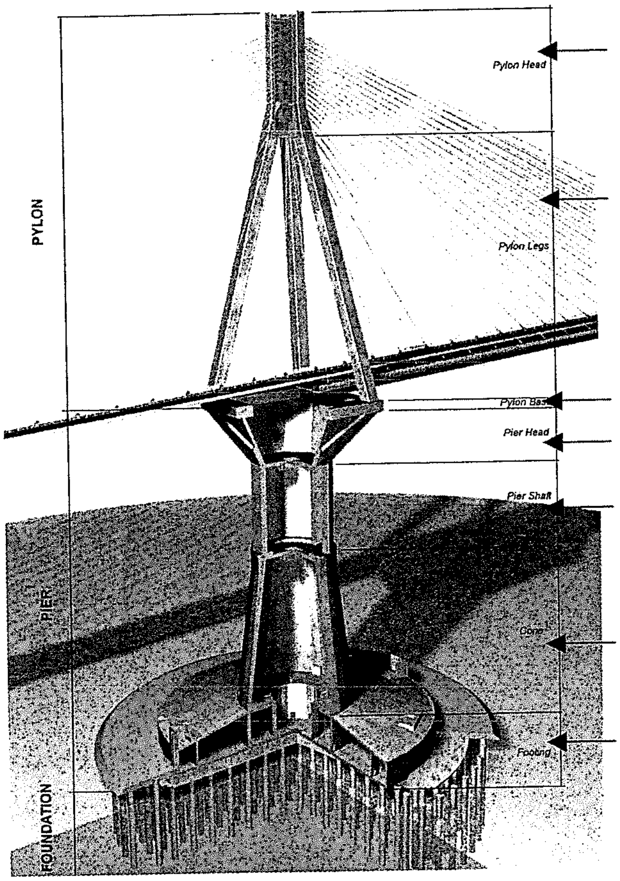
The different covers of the structure have been defined in accordance to the durability criteria selected. The following table summarizes the covers selected for the Rion-Antirion Bridge and applied throughout construction for the different exposure zones.

Table I. Covers in relation to exposure zone (values are in mm)

Exposure Situation		Contractual Specifications	Minimum Nominal Cover used
Viaducts Pile Foundations (bored or composite)		-	100
Immersed zone (below MSL –5)		50	60
Tidal & Splash (MSL –5 to MSL +10m)		75	85
Substructure externally exposed above MSL +10		50	50
Substructure over land		45	50
Bridge & Viaduct Superstructure	Deck lower free surface	40	40
	Deck upper surface	30	30

2.3 *Concrete Specifications towards Durability*

Concrete 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. The following Figure 1 presents the concrete class with the cement type for the main piers and pylons structures.



Exposure situation	**Concrete Class**	**Types of cement used**	**Max RCPT values at 90 days (Cb)**
XC4 XS1	C60/75	CEM I & CEM III	4000
XC4 XS1	C65/75	CEM I & CEM III	4000
XC4 XS1	C50/60	CEM I & CEM III	4000
XC4 XS3	C45/55	CEM III	1000
XC4 XS3	C45/55	CEM III	1000
XC4 XS2	C45/55	CEM III	2000
XC1 XS2	C45/55	CEM III	2000

Figure 1. Main piers and pylons

The types of cement are as follows:

- 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.

All concrete mixes have a maximum W/C ratio of 0.40.

3. Validation of concrete specifications

3.1 Selection of constituents

The concrete constituents have been chosen to enable a good ability to put in place the concrete in situ. The stability of concrete constituents and their properties are major factors to guarantee a constant and uniform concrete production.

3.1.1 Cements

Most of concrete mixes have been mixed with cement type CEM III 42,5 PM ES with slag content higher than 60%. The cement has been specially produced by TITAN local supplier for project requirements. This cement has a low heat of hydration and is adequate for marine exposure environments.

3.1.2 Aggregates

The chosen aggregates are crushed limestone stone and come from the quarry of Lafarge Araxos. It is divided in three fractions: coarse1 10/20, coarse2 4/10 and sand 0/4. The aggregate supplier has to supply a specific sand witch enables to regulate the fines conten around 9%. Siliceous sand could not been used because of alkali-silica reaction risks.

3.1.3 Admixtures

The admixtures have been chosen among numerous products. Optima 100 by Chryso, Glenium 27 and Rheobuilt T3 by MBT have been selected for their technical characteristics.

3.2 Concrete production

Before the beginning of daily concrete production, the moisture content of aggregate, the consistency (slump and flow) and the temperature of concrete are controlled. If the workability values agree with the conformity values and the concrete temperature is satisfactory for this seasonal period, the concrete production is proceeding.

If the values are not in agreement with the conformity values, corrective action is done by the use of ±5 litres of water per cubic meter and ±0.5 kg admixture per cubic meter. The proportion of hot/cold water is adjusted in order to obtain the required concrete temperature.

Each 100 m^3 or per construction part (if the quantity is less), samples are taken for the determination of compressive strengths. Depending on the construction's needs for information on early age, extra samples are taken (stripping of the formwork, pre-stressing etc.).

3.3 Statistical evaluation of concrete production results

On Table II the average value and standard deviation of 28 days compressive strengths per all production and per concrete class is shown (Sand Box has been used for the capping of C60/75 cylinders).

Table II. Average strengths and standard deviations by concrete class

Concrete Class	Mix number	Amount of cement (kg/m^3)	Average strength (MPa)	Standard Deviation
C40/50	416/418	450	74.4	3.7
C45/55	406	400	76.6	4.8
	425/426/428/429	420	68.6	4.8
	420	400	69.9	4.9
C50/60	520	420	75.0	3.2
	446	450	75.0	4.2
C60/75	610	490	82.0	5.0
	612	490	79.8	2.6
	620	490	80.6	2.8
	670	490	80.5	2.0

4. Durability study

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 site 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 site laboratory to satisfy experts' requirements.

4.1 Durability indicators

For all exposure zones. the main durability indicator selected is the RCPT result (Rapid Chloride Penetration Test).

This test has been performed systematically on all concrete conformity trials for each different mix defined for the structure. Then the respect of fresh concrete parameters within acceptable tolerances guarantees results on hardened concrete (strength and durability characteristics) equivalent to the ones obtained during those conformity trials.

4.2 General concrete requirements and results – all exposure zones

Laboratory results correspond to test results obtained during conformity trials in site 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.

The following Table III summarises the RCPT results of the principal mixes used on site:

Table III. RCPT results of concrete mixes used on site

Mix N°	Class of Concrete	Use of Mix	Exposure Class	Type and quantity of Cement	Dmax (mm)	W/C Ratio	RCPT Results min-max (Cb)
420	C45/55	Pier Base	Substructure below MSL +10	CEM III 400 kg/m^3	20	0.40	480-1050
432	C45/55	Raft & Walls in Dry Dock	Immersed zone below MSL –5	CEM III 450 kg/m^3	10	0.40	430-880
520	C50/60	Pylon Base	Substructure above MSL +10	CEM III 420 kg/m^3	20	0.37	200-360
610	C60/75	Pier shaft slab	Splash zone MSL –5/+10	CEM III 490 kg/m^3	20	0.33	220-390
620	C60/75	Pylon legs	Superstructure of Main Bridge	CEM III 327 kg/m^3 CEM I 163 kg/m^3	20	0.33	270-575
612	C60/75	Deck on shore	Superstructure of Main Bridge	CEM III 490 kg/m^3	20	0.33	320-370
670	C60/75	Deck off shore	Superstructure of Main Bridge	CEM I 450 kg/m^3	20	0.33	1300-2100

4.3 Validation of long-term performance of concrete

For the particular externally exposed zone below MSL +10 (immersed and splash & tidal zone), the most exposed to corrosion risk, a more 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.

4.3.1 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.

Cores have been taken and tested at different ages. More particularly, measurements have been performed on cores taken from walls cast with 425 formula of C45/55, 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).

4.3.2 Numerical simulations

The software used has already been applied to the durability of concretes from the Vasco da Gama Bridge built in the Tagus bay in Lisbon [Houdusse, Hornain and Martinet, 2000]. This software includes a mathematical model which describes the transport equation of a chemical species, and a finite element model which corresponds to the spatial discretization of the mathematical model, It has been used on PC with MATLAB.

The numerical simulations permit a variation of concrete characteristics with space and time. Furthermore, the variation of the diffusion coefficient with respect to time is the one of the most important parameter for the simulation.

The equation used to describe the evolution of this parameter corresponds to the general equations of the diffusion coefficient: $D = a\, t^{-\alpha}$ with a and α two constant values linked to the concrete used.

4.3.3 Interpretation

At different dates, the chloride profiles measured on concrete samples are compared with the numerical simulations to validate the parameters fixed in the model (evolution law of the diffusion coefficient. limit condition. capacity of chlorides fixation. ...). So a simulation is made at the requested 120 years.

The chloride threshold at the level of reinforcement (corrosion initiation) is taken equal to 0.4 %. 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.

5. Results

5.1 Laboratory results

5.1.1 LERM study results

The oxygen permeability has been measured to be $< 1.10^{-17}$ m^2 at 28 days. The chloride diffusivity has been measured to be $< 1.10^{-12}$ m^2/s at 28 days and $< 5.10^{-13}$ m^2/s after 4 months. Those results show already a good ability of concrete to prevent chloride migration. On the same time, the chloride binding capacity of the cement paste has been evaluated. The results show that the capacity of chloride fixation by the binder is relatively high approximately 50 % of the total chlorides present in the paste with a maximum value about 1%.

The Figure 2 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 4.3.2. The equation is as follow: $D = 1.10^{-12}\, t^{-0.4297}$.

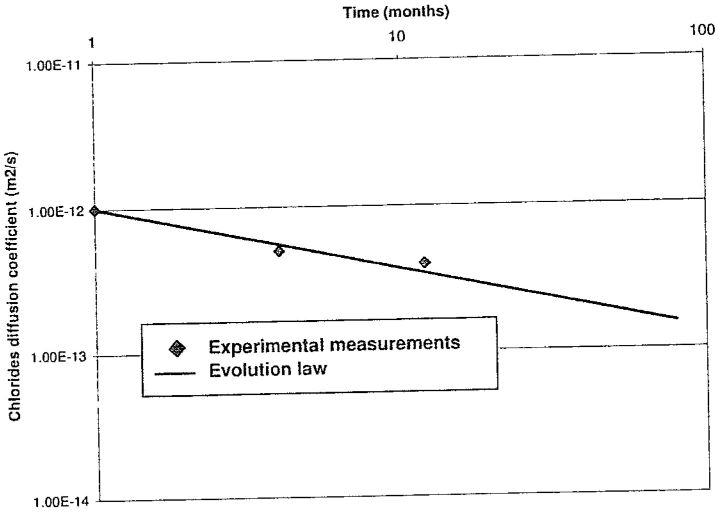


Figure 2. Evolution law of chlorides diffusion coefficient with time

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

The simulations carried out by LERM allowed presenting 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 $D = 1.10^{-13}$ m^2/s at 10 years has been used. Indeed, the decrease of this coefficient then after is less significant. Furthermore the value taken for the calculations is thus conservative.

The chloride profiles obtained 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 $D = 1.10^{-13}$ m^2/s.

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

5.1.2 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 adequacy of laboratory concrete with in-situ concrete.

Indeed, during mix design and conformity trial mixes 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.

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 (like 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, etc. 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 here below:

Table IV. Site results

Mix N°	Date of casting	Exposure Zone	RCPT results on production samples	RCPT laboratory results on the same formula
406	7/12/99	Immersed Zone (below MSL - 5.0)	697	480 - 1050
429	11/04/00 28/03/00	Immersed Zone (below MSL - 5.0)	670-763-786 635-590	650 - 1040
446	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.

5.2 Assessment of homogeneity of in situ concrete

In order to validate the uniformity of in-situ concrete compared to laboratory one, non-destructive testing have been performed on the 4 piers in splash zone (inside of the first lift of the pier shaft). Two methods are used to get precision in the results: the sclerometer and the ultra sonic (pulse velocity).

The sclerometer measures the surface hardness of the concrete by the determination of the rebound number using a spring-driven steel hammer. The ultrasonic auscultation is the measurement of the sonic wave transmission time in concrete and is in relation with the homogeneity and the cracking of the materials.

The objective of this program is to determine the classification of different compacity areas (low, medium, high): one zone of each face of the octogon has been investigated (8 zones x 4 piers = 32 zones). The area of each testing zone has been in order of 6 m^2. Some cores (6 per location) have been extracted by site laboratory from the piers to be submitted to chloride diffusion coefficient measurements and RCPT tests (see Table V).

From the results, we can see that the variation of the diffusion coefficient in the different compacity zones is very similar to the variation of the test itself (differences between the three cores of one given zone). In addition, the RCPT results are similar from one zone to another. This tends to demonstrate the good homogeneity of the in situ concrete.

Table V. In situ chloride diffusion coefficient (D) and RCPT results

Pier	Construction age (month)	Compacity zone	Mean value of D (10E^{-12} m^2/s)	Standard deviation of 3 cores (10E^{-12} m^2/s)	Standard deviation of the 11 measurements (10E^{-12} m^2/s)	Min-max value (10E^{-12} m^2/s)
M1	24	medium	0.53	0.21	0.27	0.22-0.98
		low	0.74	0.41		
M2	21	medium	0.22	0.05		
		low	0.26	0.11		
M3	36	medium	0.38	0.07		
		low	0.30	0.17		
M4	33	medium	0.32	0.20		
		low	0.71	0.29		

Pier	Construction age (month)	Compacity zone	Mean value of RCPT measurements (Cb)	Standard deviation between the 3 cores (Cb)	Standard deviation of the 11 measurements (Cb)	Min-max value (Cb)
M1	24	medium	269	12	41	221-365
		low	292	32		
M2	21	medium	331	38		
		low	221	4		
M3	36	medium	260	35		
		low	289	51		
M4	33	medium	242	69		
		low	278	184		

Furthermore, those results have provided additional data for numerical simulations of expected service life.

5.3 Assessment of long term chloride diffusion coefficient

These additional cores taken in the in situ concrete structure have been used by LERM in order to perform additional measures of Diffusion Coefficient, at latest ages, and to reinforce the assumption on the α value of the equation of evolution of the Diffusion coefficient, and hence on its long-term value.

In the same way, during the construction phase, one reinforced concrete panel in-situ has been cast during real pour of structural concrete with the same formula. the same concrete staff and kept under the same conditions as real structure. The element has been poured on P2 pile cap in Rion side, with dimension of 1 m high by 5 m long and 0.5 m wide, with reinforcement of Ø20 mm every 200 mm and cover of 50 mm minimum on the two sides. The panel is kept in marine environment once the embankment between P2 and P3 is removed.

This panel allows performing measurements of the real chloride ingress at different ages, even after the construction period. The concrete panel could also be used to obtain additional points in the evolution curve of Diffusion Coefficient, and reinforce again the equation proposed by the LERM. LERM laboratory performs at the same age on reinforced wall the measurement of chloride diffusion coefficient under electric field (3 measures by age) and the total and free chloride measurement (measurement at 5 depths by age).

The first part of four concrete cores have been extracted from the durability wall in October 2004 and analysed in LERM laboratory for the measurement at point zero. These measurements will be done at 10 different ages: 6 months, 1 year, 2, 5, 10, 15, 20, 25, 30 and 35 years. The follow-up program of testing is included in the Maintenance Manual of the Bridge.

Thus, the results of diffusion coefficient for the medium compacity zone of each pier and for concrete cores from reinforced wall have been used in order to validate the evolution of diffusion coefficient with respect to time.

The values have been reported in the curve of diffusion law according the general equation for the evolution of the diffusion coefficient (see graph presented below). So, the law currently considered to achieve the numerical simulation is as follow: $D = 1.10^{-12}.t^{-0.2868}$.

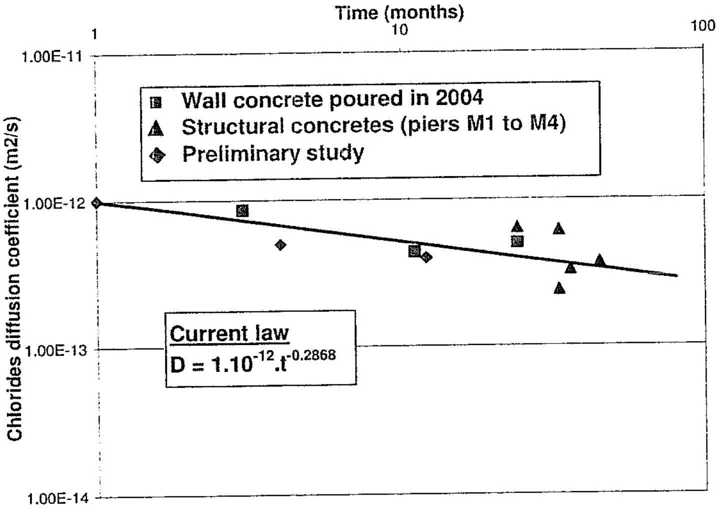


Figure 3. Curent diffusion law

5.4 Comparison of real chloride ingress and simulated values

5.4.1 Durability wall

The reinforced wall concrete has already been studied at three ages: 3, 11 and 24 months. The total chlorides profiles measured are given in Figure 4 below. These results show a significant increase of chlorides content only in the first 20 mm from the surface.

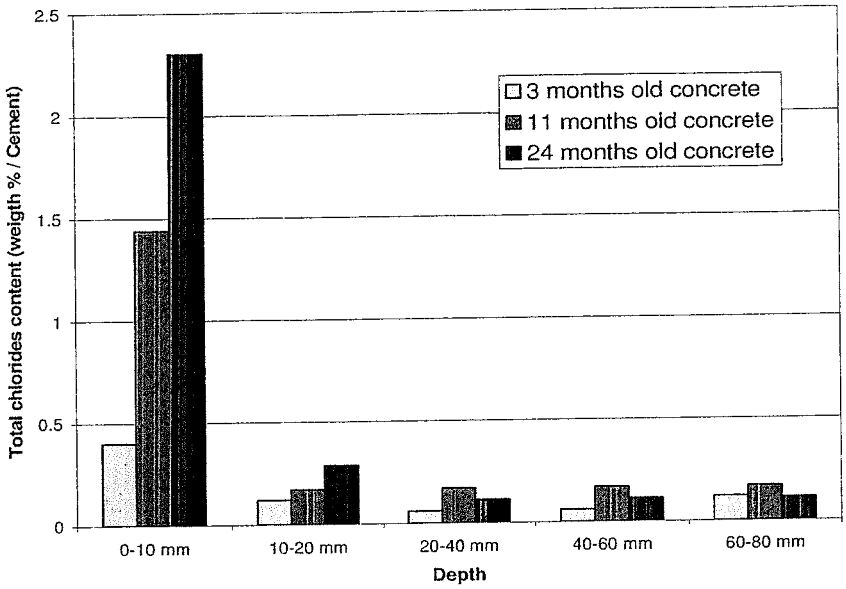


Figure 4

So, the numerical simulations have been made with the current law of diffusion coefficient evolution, and with a limit condition about 3.5%/kg of cement based on experimental results. The results of numerical simulations have been obtained at the ages of 24 months and 120 years (service life). The results obtained show that the concrete from reinforced wall complies with the durability requirement of 120 years with regard to the corrosion risk because the free chlorides content is under the threshold of 0.4% (of cement).

5.4.2 Pier M2

In the same way, numerical simulations have been made on structural concrete from pear M2 (age: 45 months) to validate the conclusions obtained on concrete from reinforced wall. These simulations have also been achieved with the current law of diffusion coefficient evolution, and with a limit condition about 3.5%. The results obtained show that the structural concrete also complies with the durability requirement of 120 years with regard to the corrosion risk.

6. Conclusions

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 120 years service life. A follow up of in situ concrete with same testing has been carried out to confirm its quality towards durability requirements and to obtain more results allowing the verification of service life assessment.

7. References

Houdusse O.. Hornain H. and Martinet G. (2000) Prediction of Long-Term Durability of Vasco Da Gama Bridge in Lisbon. *Fifth International Conference of CANMET/ACI. Barcelona. 1037.*