INFLUENCE OF SEAWATER CURING ON REINFORCED CONCRETE

Application to the case of floating caissons

CENTRAL LABORATORY FOR STRUCTURES AND MATERIALS

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MINISTERIO DE TRANSPORTES Y MOVILIDAD SOSTENIBLE
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CEDEX
CENTRO DE ESTUDIOS Y EXPERIMENTACIÓN DE OBRAS PÚBLICAS
Puertos del Estado

INFLUENCE OF SEAWATER CURING ON REINFORCED CONCRETE APPLICATION TO THE CASE OF FLOATING CAISSONS

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“Puertos del Estado” (State Ports) have within its competencies stablished in the “Texto refundido de la Ley de Puertos del Estado y de la Marina Mercante” (Revised Text of The State Ports and Merchant Navy Act) to promote the investigation and technical development in subjects related to port economics, management, logistics and engineering.

This publication is part of this effort to ensure that Spanish port engineering continues being an international benchmark. And, more specifically, it is the result of the work that, within the framework of the assignment given by State Ports to the “Centro de Estudios y de Experimentación de Obras Públicas” (CEDEX), which is part of the Ministry of Transport and Sustainable Mobility, it is carries out for technical assistance, applied research and technological development in matters of interest for the port system of general interest.

Reinforced concrete caissons are used for the construction of marine works as breakwaters and docks. In Spain, they are normally made with the sliding framework technique on a floating platform, and then transported, generally afloat, from the construction site to their final location, where they are anchored and filled. During the construction of the caissons in the floating platform, the reinforced concrete being built is progressively submerged in seawater while the upper part is gradually concreted by sliding the formwork. This system has clear constructive and economic advantages, but it entails that the concrete of the caisson, which will remain underwater in its final location, comes into contact with seawater at very early ages, which could lead to question the durability of the structure.

Despite the wide experience that Spanish engineering has accumulated over decades in the use of this execution procedure, with clearly positives results in terms of the quality of the works carried out, the regulation applied to these structures, either Spanish or international, have for years not included explicit references to this constructive typology, particularly regarding the possibility of curing reinforced concrete with seawater.

By request of State Ports, CEDEX has been working in recent years on studies related to this process of construction with sliding formworks on floating platforms, which forces the concrete to come into contact with seawater without prior curing with fresh water, obtaining as preliminary results that this technique is not considered to have a negative influence on the risk of corrosion of the reinforcement, as long as it is carried out correctly.

As result of this preliminary work developed by CEDEX, the recently published Structural Code included the possibility, sufficiently justified, of curing with seawater in reinforced concrete elements that will remain permanently located in XS2 environment (submerged areas of docks, breakwaters and other coastal defense works).

This publication summarizes the work carried out with concrete, both in the field with caissons built and in service, and in the laboratory, concluding that there is no significant risk of increased corrosion of the reinforcement due to the construction process of caissons on floating platforms.

The main conclusion of this work, included in this document, is considered of great importance to ensure the quality of our infrastructures, and may also serve to export Spanish caisson manufacturing technology abroad, technically assuring its characteristics. Moreover, this work reinforces the commitment of State Ports to research and development in port engineering to keep improving the development and competitiveness of our ports.

ÁLVARO RODRÍGUEZ DAPENA
PRESIDENTE DE PUERTOS DEL ESTADO

The Centre for Studies and Experimentation in Public Works (CEDEX) is a prominent public body whose main purpose is to address new and traditional challenges in the field of public works, transportation, environment, and climate change, contributing to the advance of applied knowledge and in the introduction and spreading of innovation.

This mission is materialized through its different centres and laboratories which, specialized in different fields of expertise, provide their service both to private companies as well for public bodies of which CEDEX is an own means.

This publication is the result of Technical Assistance, Applied Research and Technological Development that CEDEX, through the Central Laboratory of Structures and Materials, provides to The Spanish National Ports Authority (State Ports) to give answers to matters that are of interest to the State-owned Port System.

The floating caisson system is a procedure widely used in Spain to construct breakwaters and docks. This system has constructive and economic advantages, but it means that the concrete, which will be permanently submerged during its service life, has been exposed to seawater prematurely during its construction, which may lead to question the future durability of the caisson due to an increased risk of corrosion of the reinforcement.

The origin of this publication dates to 2009, when the Central Laboratory of Structures and Materials of CEDEX completed, at the request of State Ports, a first study on the influence on the durability of submerged concrete as a result of premature contact with chlorides after its execution. In 2018, State Ports commissioned CEDEX to complete this research with a second, more far-reaching study, carrying out a wide range of laboratory tests lasting up to 4.5 years, as well as an evaluation of floating caissons placed in the ports. This publication brings together the most significant results and conclusions reached at CEDEX after all the studies carried out.

The rigorous and very complete study carried out has led to the conclusion that there is no significant risk of corrosion of the reinforcement due to the construction process of the caissons on a floating platform. The results achieved are of maximum interest as they solve a real problem and guarantee the durability of caissons built with this technology. Therefore, this document becomes a valuable technical tool for Spanish Ports, since it ensures the durability of their structures, and for Spanish construction companies, which are an international reference in this technology, and will find in this publication a technical endorsement to be able to apply it in other countries.

Finally, this work has also allowed the improvement of national technical regulations. The validation of this technique from the point of view of durability has been included both in the Structural Code and in the Handbook for the Design and Execution of Floating Caissons in Port Works.

CEDEX would like to thank State Ports for their interest in expanding the current state of knowledge in all matters concerning the corrosion pathologies of concrete exposed to marine environment and for entrusting the Central Laboratory of Structures and Materials of CEDEX to carry out this task.

We would also like to thank the various Port Authorities that participated in this work for their trust in CEDEX and for their support, which enabled us to carry out the work on their floating caisson docks successfully.

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INDEX

INDEX OF FIGURES

INDEX OF TABLES

INDEX OF PHOTOGRAPHIES

1 INTRODUCTION

The floating caisson system is a recent construction procedure widely used in Spain for the construction of breakwaters and docks. It is based on the construction of large reinforced concrete caissons on floating platforms. The procedure uses a platform with a sliding formwork that gradually rises to construct the caisson shaft. As the formwork slides, the concreted caisson strip is gradually submerged in the sea just a few hours after its manufacture. Once finished, they are kept afloat until their subsequent immersion at the final location.

Photograph 1. floating platform with a caisson in construction, partially submerged

Photograph 2. Caisson at the final location in the breakwater

This system (Photograph 1 and Photograph 2) offers significant economic and constructive advantages. Nevertheless, the construction process puts the concrete into premature contact with seawater, which calls the durability of the caisson into question due to the increased risk of corrosion that this entails for the reinforcements.

However, there is little research on the effect of seawater curing on concrete [1][2][3] intended to remain in the XS2 environment (under seawater). The literature evaluated agrees, indicating that the differences found in the depth reached by chlorides in concretes with different freshwater curing periods (7 and 28 days) are not significant [1]. Indeed, the differences in chloride depths are less than10 mm when compared with specimens placed directly in contact with seawater after demoulding. Moreover, some studies [3] identify the absence of curing (allowing the concrete to dry) before the final seawater immersion as more detrimental than the actual contact with seawater itself.

Although the few existing studies show positive results, international standards [4][5] are very conservative on this matter, and they advise against putting reinforced or prestressed concrete in contact with seawater until it has reached 90% of its strength.

This paper shows the research carried out by CEDEX, both in the laboratory and in on-site studies, to determine the extent to which premature contact with seawater affects steel corrosion in the XS2 environment.

2 LABORATORY STUDY: EFFECT OF SEAWATER CURING ON CONCRETE IN SUBMERGED MARINE ENVIRONMENTS (XS2)

The Spanish standard (Structural Code, [6]) requires concrete curing during the first days after its casting. In marine structures with harsh environmental conditions, the Spanish standard recommends curing for up to 7 or 11 days for CEM I, ordinary Portland cement (OPC), and CEM III, Portland cement with blast-furnace slag (BFS), respectively.

With this in mind, the CEDEX laboratory research tries to compare the behaviour of concrete cured for 11 days in fresh water before being submerged in seawater with concrete submerged directly in seawater 24 hours after its casting.

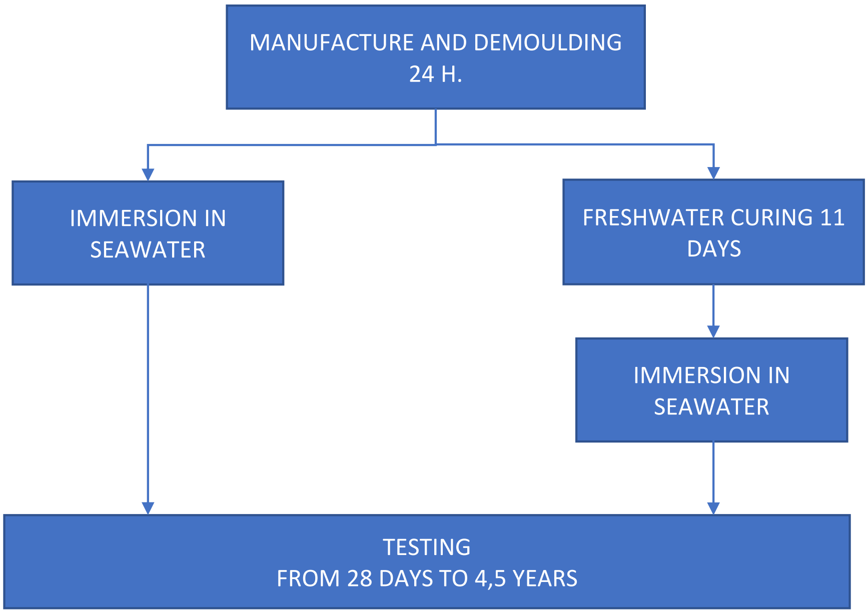


Figure 1. Different curing methods implemented in laboratory study

Three different concrete mixtures were tested, using three different cements: an ordinary Portland cement (OPC or CEM I), a cement with a fly ash (FA) content of between 21% and 35% (CEM II/B-V), and a cement with a blast-furnace slag (BFS) content of between 66% and 80% (CEM III/B). These three mixtures comply with the most restrictive mix proportioning requirements for concrete in marine environments (XS3). Table 1 shows the characteristics of these concretes. In addition, whenever possible, the results were completed with those obtained in the previous CEDEX study, carried out in 2009 [7], the characteristics of which are also listed in Table 1.

Table 1. Characteristics of concretes tested
CEDEX (2009 and 2022)

	CEDEX 2022 Research			CEDEX 2009 Research			
Designation	CEM I (OPC)	CEM II (FA)	CEM III (BFS)	H-obra (OPC)	H-0,45 (OPC)	H-0,40 (OPC)	H-0,40 SF (OPC+SF)
W/b Ratio	0,45	0,45	0,45	0,45	0,45	0,40	0,40
Type of cement	CEM I 42,5 R	CEM II / B-V 32,5 R	CEM III / B32,5 N-SR	CEM I 42,5 N/SR	CEM I 42,5 R/SR	CEM I 42,5 R/SR	CEM I 42,5 R /SR+SF
Cement Weight	350 kg	350 kg	350 kg	395 kg	400 kg	400 kg	396 kg +44 kg SF
Curing time	11 days	11 days	11 days	7 days	28 days	28 days	28 days

2.1 COMPRESSIVE STRENGTH AND PERMEABILITY

Figure 2 shows the compressive strength [8] obtained in both CEDEX studies from 2009 and 2022, comparing the results from specimens cured with fresh water with those from specimens cured with seawater.

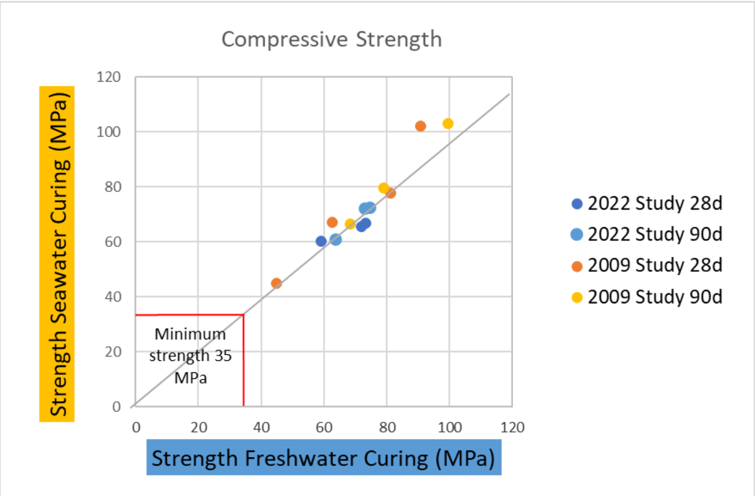


Figure 2. Compressive strength, comparing seawater and freshwater curing methods. 2009 and 2022 research

The different concretes were mixed to meet the requirements of the harshest environment, XS3, where the minimum strength required by the Spanish standard (Structural Code) is 35 MPa. All the concrete tested reached the minimum requirement.

Moreover, equivalent results were obtained for specimens cured with fresh water (abscissa) and seawater (ordinate), indicating that **premature contact with seawater has no influence on the compressive strength**.

In the same way, Figure 3 shows the permeability of concrete obtained in the water penetration test [9]. For each concrete tested, the figure shows the maximum water penetration depth obtained when it is cured with seawater against the same result when concrete is cured with fresh water.

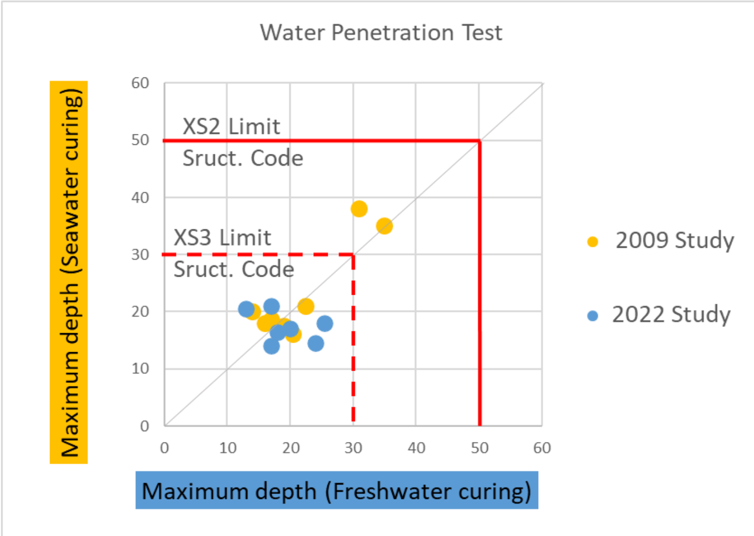


Figure 3. Maximum water penetration depth. Seawater and freshwater curing. 2009 and 2022 research

Similar water penetration results were obtained for different curing conditions. All the concretes meet the requirements of the Structural Code for environment XS3 (≤ 30 mm), the strictest, except for the specimens taken directly on site (CEDEX 2009 study). Unlike the compressive strength results, which reflect quite different qualities of concrete, the water penetration results appear, except for one concrete, grouped in a cloud of points around the line of equality cured with fresh water-sea water, with a range of maximum penetrations from 15 to 25 mm.

2.2 RESISTANCE OF CONCRETE TO CHLORIDE INGRESS

The concrete specimens were kept submerged in seawater for three years for the OPC and four and a half years for the FA and BFS cements. The chloride penetration depth during that period was measured at different ages following the colorimetric method of Collepardi et al. [10] by staining the fracture surface of 20 cm cubic specimens with $AgNO_3$ and measuring the depth of chloride penetration that the colourless surface indicates (Photograph 3).

Photograph 3. Depth of chloride penetration after staining the fracture

Figure 4 to 6 show the results obtained. The first conclusion is clear: the proper selection of the binder is more important than the curing method carried out. Chloride penetration is much higher in OPC than in cements with FA and BFS (CEM II/B-V and CEM III/B), even when comparing the OPC, 11 days freshwater cured, with the other cement types cured exclusively in seawater.

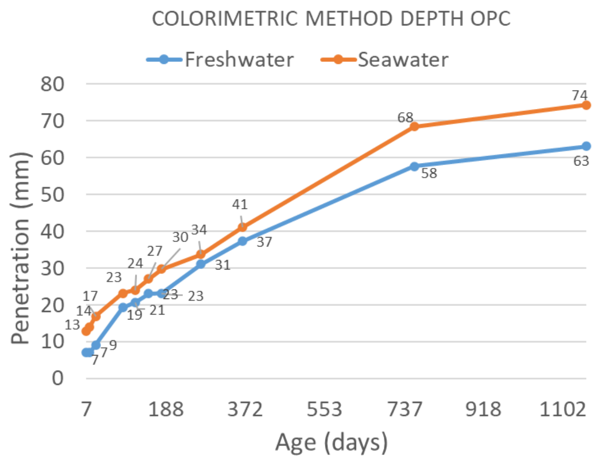


Figure 4. Chloride depth. Ordinary Portland cement (**CEM I**). 2023

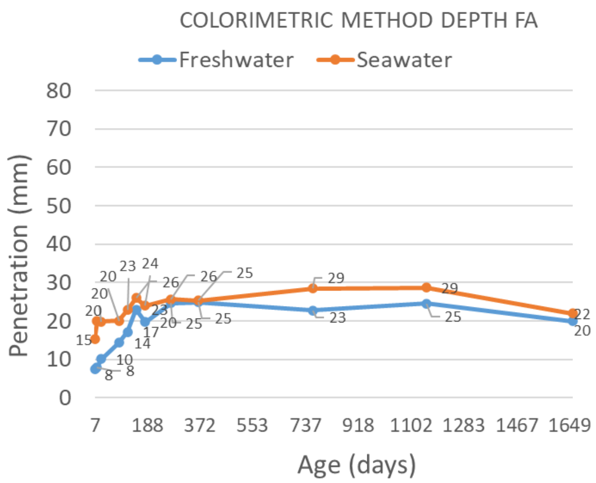


Figure 5. Chloride depth. Fly ash cement (**CEM II**). 2023

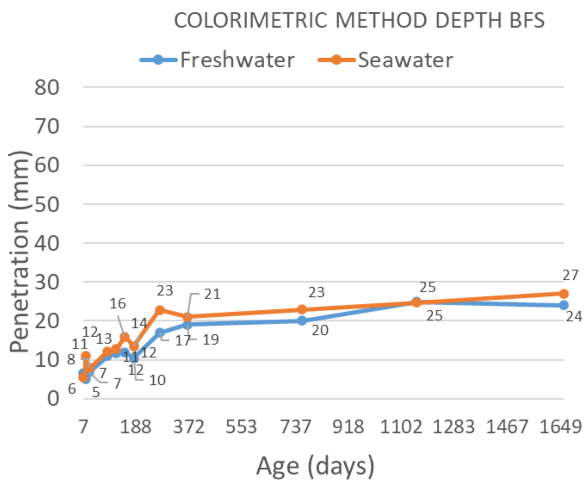


Figure 6. Chloride depth. Blast-furnace slag cement (**CEM III**). 2023

To evaluate the performance against chlorides in relation to the type of curing, the depths reached are also represented as a function of the square root of time (Figure 7 to Figure 9). Considering that chlorides advance in concrete with the square root of time (good linear fit), it is expected that the impact of the initial curing type, evaluated during the first three years, should not vary appreciably over time.

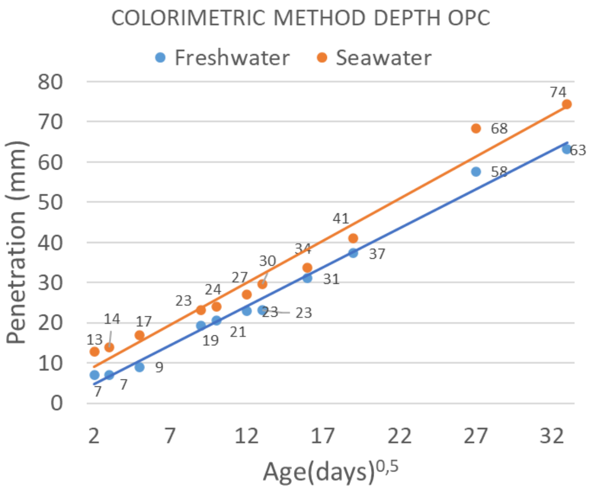


Figure 7. Chloride depth. Ordinary Portland cement (**CEM I**).2023. **Square root of time**

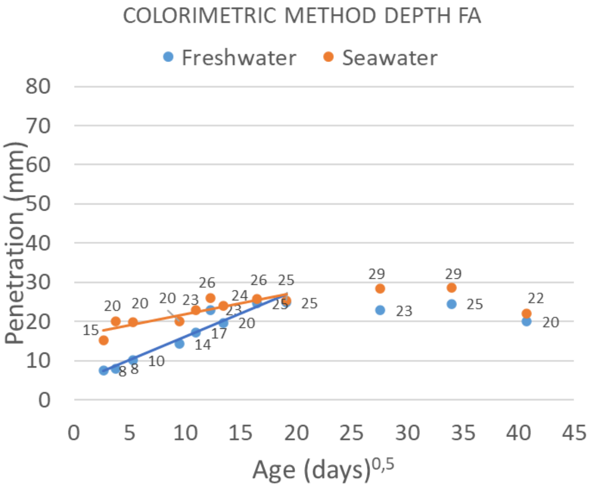


Figure 8. Chloride depth. Fly ash cement (**CEM II**). 2023. **Square root of time**

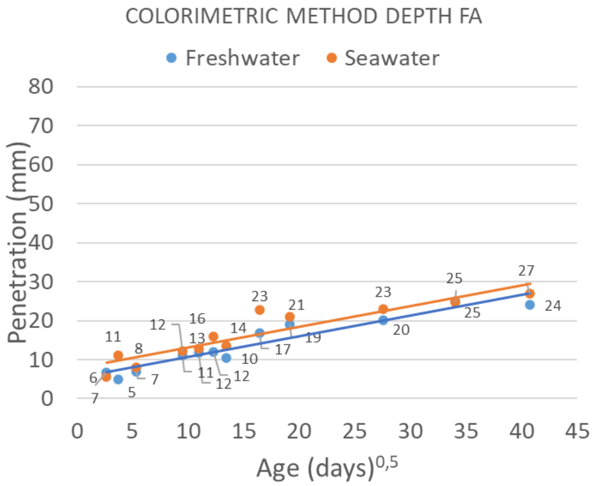


Figure 9. Chloride depth. Blast-furnace slag cement (**CEM III**). 2023. **Square root of time**

If we evaluate according to the curing procedure, the smallest difference is found in concrete made with BFS (Figure 9). The high capacity of slags to combine chlorides, already described in other works on seawater curing [11] explains this satisfactory performance against chloride diffusion from early ages, regardless of whether it is cured with freshwater or seawater.

In both OPC and FA, the difference between curing methods is up to eight to twelve millimetres in depth in the first twenty-eight days. However, in the case of FA mixture, this gap decreases with time, and after a year, both curing treatments show similar behaviour. On the other hand, in OPC, the difference between curing methods is maintained over time, not exceeding 11 millimetres during the first three years of exposure to chlorides.

After analysing the results achieved in 2023, the assessment can be completed with the results obtained in 2009 with freshwater curing periods up to 28 days. For this purpose, Figure 10 presents both studies together, showing the penetration of chlorides in concrete cured with seawater versus the penetration of chlorides in the same concrete initially cured with fresh water.

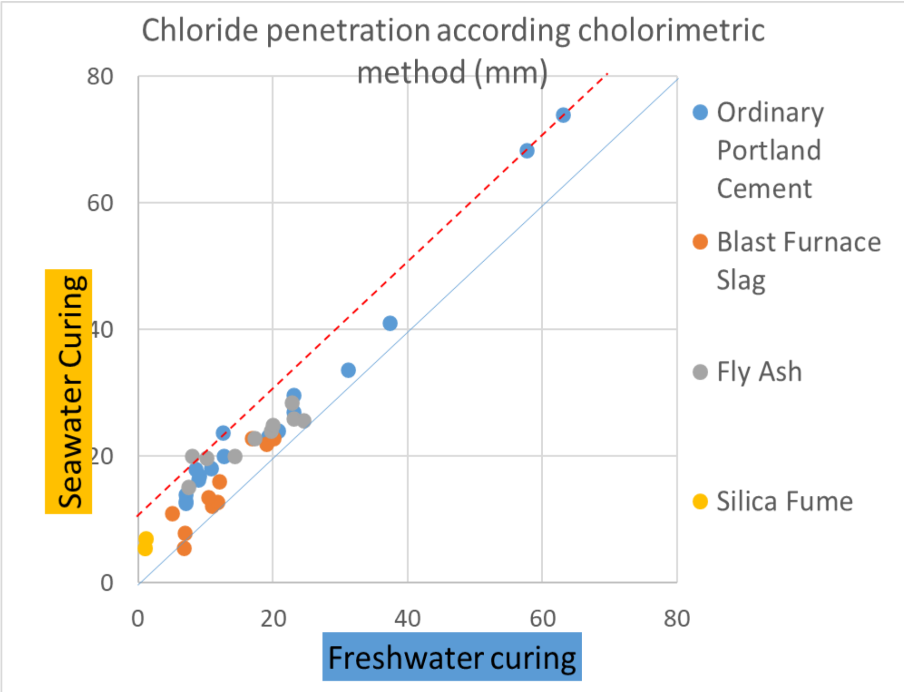


Figure 10. Chloride penetration according to colorimetric method in freshwater and seawater-cured concrete (2022 and 2009)

Both test campaigns provide remarkably comparable results. Silica fume concrete shows exceptionally low chloride penetration, proper to its low permeability. The BFS gets closer to the equality line regardless of the age of the concrete. In the case of FA, as time increases (higher chloride penetration depths), the behaviour of concrete cured with freshwater and seawater becomes closer. And finally, in the case of OPC, there is a clear tendency to maintain a difference of around 10 mm, depending on the curing procedure, even with chloride penetrations greater than 5 cm deep.

Therefore, **according to the experimental results achieved in this study (Figure 10), complying with the mix design and permeability requirements of the Structural Code for concrete in XS3 environment, and using CEM II/B-V, CEM II/A-D or CEM III/B as binder would be sufficient to ensure that the corrosion durability of the floating caissons is not diminished by the early immersion of the concrete that will be definitively submerged under seawater.**

In addition, Article 43 of the Structural Code considers that CEM III/A, concretes with more than 6% silica fume or 20% fly ash, as well as CEM IV that give the concrete this same content of pozzolanic addition, are just as effective in protecting reinforcements against chloride corrosion as the three cements with additions studied in this document. Consequently, the conclusions previously showed can be extended to these cements.

Finally, if it is not possible to use the cements described above, increasing the coating by 10 mm will ensure that the concrete of the floating caissons will have a performance against chlorides at least equivalent to that of the same concrete previously cured with fresh water, provided that the permeability and mix design for XS3 environment (Structural Code) are maintained. In the case of

using other less demanding mix designs, a specific experimental study will be necessary, as currently required by Spanish regulations (Structural Code[1]).

In addition to using colorimetric tests to evaluate the behaviour of concrete against chlorides, complete chloride concentration profiles were obtained from the different concretes (Photograph 4 and Photograph 5) after one year immersed in seawater [12].

Photograph 4. In red, the area from where the chloride profile will be extracted

Photograph 5. Sample for chloride profile testing. Each band is cut and analysed to determine the chloride content

The results obtained are shown in Figure 11 to Figure 13.

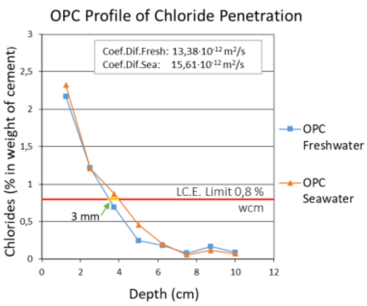


Figure 11. Profile of chloride concentration in **OPC** (1 year). 2022

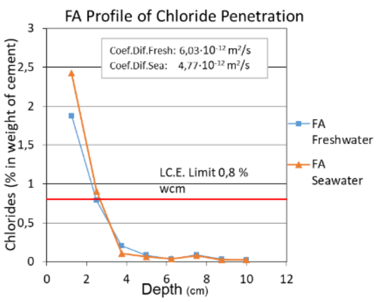


Figure 12. Profile of chloride concentration in **FA** (1 year). 2022

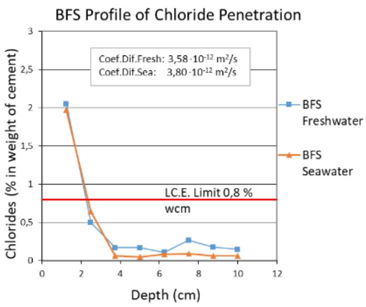


Figure 13. Profile of chloride concentration in **BFS** (1year). 2022

Again, we can see that the difference obtained using OPC is higher than by curing with seawater. The chloride threshold for the initiation of corrosion in the XS2 environment (0.8% by weight of cement, according to the Structural Code) is also shown. At one year, the greatest difference in the depth that the chloride threshold reached is found in concrete with OPC (3 mm). In concretes with supplementary

[1] **Article 29. Structural Code**: Whenever it is expressly justified by the project, through a documentary study and the decisions made regarding durability (type of cement, coatings, etc.), or through an experimental study of durability, curing by immersion in seawater may be applied in reinforced concrete elements that are going to be permanently located in exposure class XS2, avoiding concrete drying cycles throughout the process.

Comments to Article 29 by The Permanent Concrete Commission: seawater curing is restricted to concrete immersion processes after stripping the formwork without allowing it to dry at any time. Such is the case, for example, of the construction of caissons on a floating platform, a technique in which a sliding formwork is used, and the already concreted strip of the caisson is submerged in the water after sliding.

cementitious materials, the depths of the chloride thresholds are practically the same, regardless of whether they have been cured with seawater or freshwater.

For the FA and BFS samples, we also obtained the complete chloride concentration profiles after two years of immersion in seawater. Once again, remarkably similar chloride penetration profiles were obtained and the chloride depth does not vary by more than 5 mm when a different type of curing is used.

Moreover, these profiles helped us to estimate the mean turning point of silver nitrate for all the tests carried out (0.98% of total chlorides by weight of cement), a concentration similar to that obtained in other studies [13].

2.3 OTHER PROPERTIES OF CONCRETE: POROSITY AND CAPILLARY ABSORPTION

Open porosity [14] and capillary [15] tests were performed with the three different concretes and for the different curing methods.

The open porosity of the concrete was analysed by comparing the samples cured with freshwater and seawater (Figure 14).

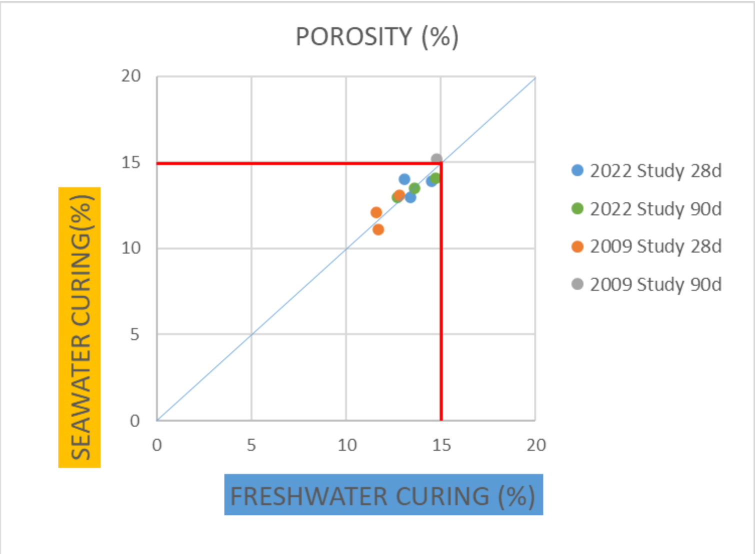


Figure 14. Results of porosity in XY graph for the different types of curing and age of the samples

The results obtained for all the concretes tested are not influenced by seawater curing. The results are between 11% and 15%, all below the threshold set by CEF-FIB Bulletin 243 for low porosity concretes [16].

During the construction of the caissons, a period of one to three days elapses between the removal of the formwork and the first contact with seawater. During this time, concrete drying should be avoided. Capillary suction tests were carried out to evaluate what would happen if concrete dried out before seawater immersion.

Photograph 6. Close-up of the specimens in contact with water for the capillary suction test

Photograph 7. Close-up of the spacers used to elevate the specimens and promote absorption

One side of the specimen is saturated by capillary suction as if the caisson's concrete had just been cast. Next, the concrete is dried for 17 h at 40ºC, creating an accelerated process similar to not curing the concrete during the 1–3-day period prior to its immersion in seawater. The moisture lost is represented by descending lines in Figure 15 to Figure 17. After this drying procedure, the same side of the specimen is put in contact with seawater for 6 hours (Photograph 6 and Photograph 7), and another weight measurement is taken (increasing lines in Figure 15 to Figure 17).

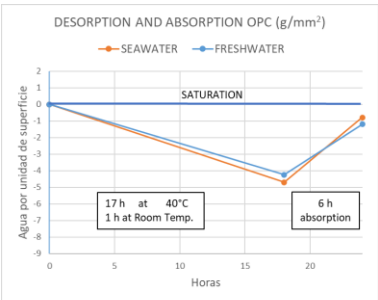


Figure 15. Capillary absorption to saturation, desorption 17h at 40ºC and 6 hours absorption for OPC

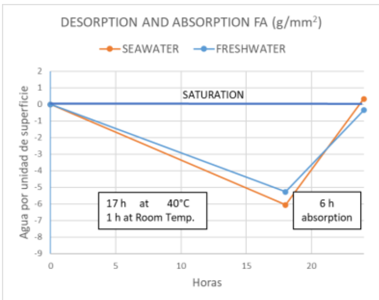


Figure 16. Capillary absorption to saturation, desorption 17h at 40ºC and 6 hours absorption for FA

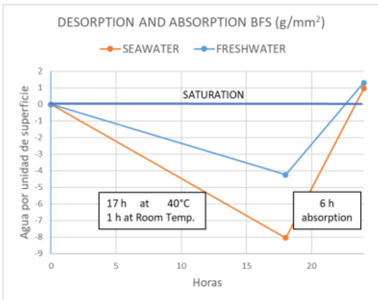


Figure 17. Capillary absorption to saturation, desorption 17h at 40ºC and 6 hours absorption for BFS

Therefore, Figure 15 to 17 show how, if the concrete is not cured before seawater immersion, it will lose some of its capillary water and then, subsequently, when the concrete is finally immersed in seawater, it will recover the lost water, although now that water will be rich in chlorides. Consequently, much higher chloride concentrations will be reached in the outer centimetres than would be achieved if the concrete were saturated with fresh water before being introduced into seawater since, in the latter case, the chlorides would only permeate by diffusion. **Hence, the importance of avoiding drying of the concrete before it is submerged in seawater. Moreover, this requirement is included in Spanish Structural Code** (footnote 1, page 14).

Photograph 8 is an example of the concreted caisson strip being cured after its manufacture before being submerged in the sea.

Photograph 8. Example of the curing process during the construction of caisson on a floating platform [17]

3 ON-SITE STUDY: INFLUENCE OF SEAWATER CURING ON REAL DOCKS IN AN XS2 ENVIRONMENT

In order to determine the influence, in an XS2 environment, of seawater curing on real docks, five caissons were tested, three belonging to the Port of Barcelona and two from the Port of Granadilla (Tenerife Island), Table 2.

Table 2. Characteristics of the caissons

	Barcelona (BEST's dock. El Prat)			Tenerife (Granadilla's harbour)	
Concrete location	Caisson 19	Caisson 20	Caisson D	Caisson 17	Caisson 18
Fabrication year	2006	2006	2008	2016	2016
Concrete typification	HA-35/P/20/IIIb+Qb+E			HA-35/F/20/IIIc+Qb+E	
Docking time	>15 days	>15 days	> 9 months	>30 days	>30 days
Coating	5 cm	5 cm	5 cm	6 cm	6 cm

Concrete samples were drilled and extracted from the top of the dock so that the boreholes were located behind the steel reinforcement of the outer face of the caissons (Figure 18 and Photograph 9).

Once extracted (Photograph 10), the upper and lower parts of each concrete core were compared. The upper part did not come into contact with seawater until the caisson was anchored in its final location, at least 15 days after demoulding (Table 2). However, once the caisson is anchored in place, this test area must be at a sufficient depth to ensure that the concrete is kept submerged (an XS2 environment). The lower part of the cores was submerged during the caisson construction process and in its final location (Figure 19).

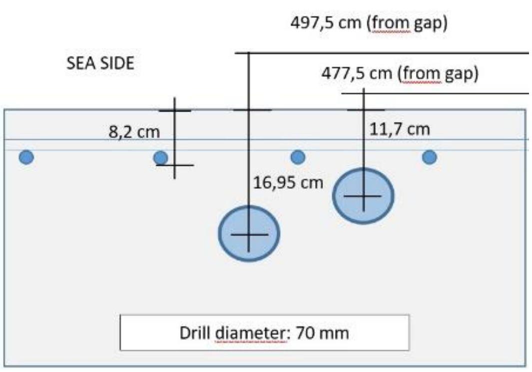


Figure 18. Drill location

Photograph 9. In situ drill location

Photograph 10. Extraction of specimens in Barcelona Port

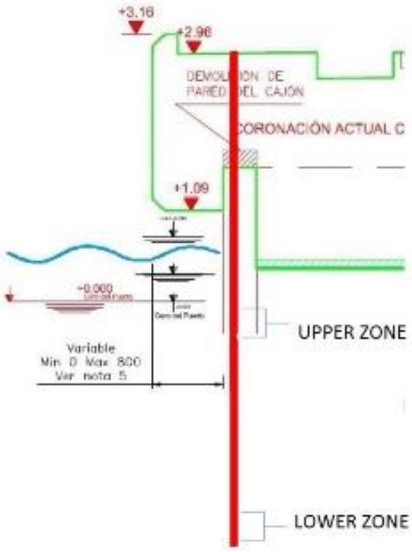


Figure 19. Different zones of study

Therefore, we will compare the concrete of the upper zone, which does not come into contact with seawater for at least 15 days, with that of the lower zone, which is submerged in seawater during the construction process. Both areas are placed in an XS2 environment once the caisson is at its final location.

3.1 COMPRESSIVE STRENGTH AND PERMEABILITY

Figure 20 shows the compressive strength results, comparing the upper and lower part of each core.

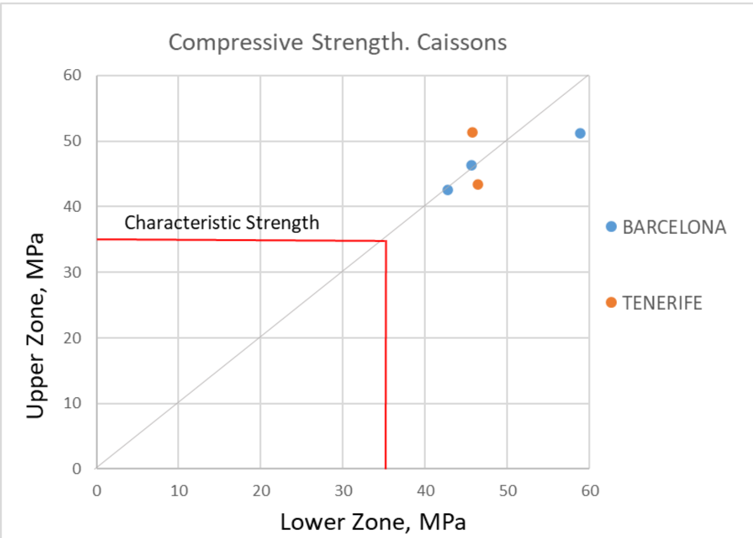


Figure 20. Compressive Strength. Comparison of UPPER and LOWER concrete

All the results are clearly higher than the design compressive strength. In addition, equivalent results were obtained from both areas, regardless of the time it took for them to be in contact with seawater. Thus, we can confirm **that premature seawater contact has no influence on compressive strength.**

Figure 21 shows the permeability of concrete obtained in the water penetration test (maximum water penetration depth).

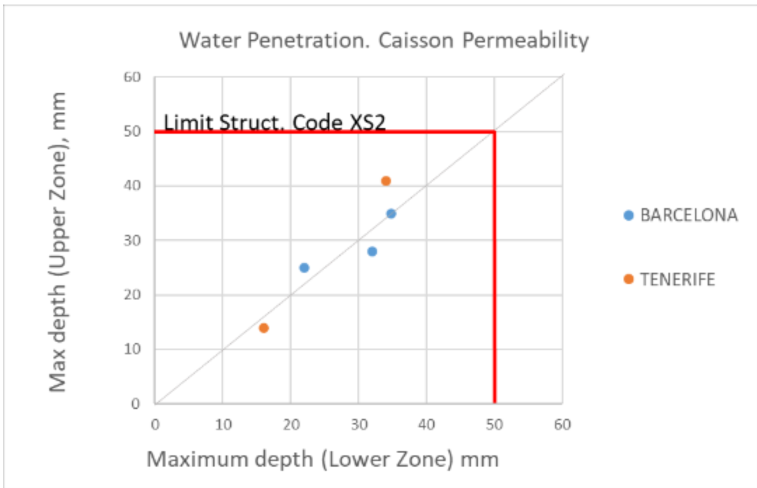
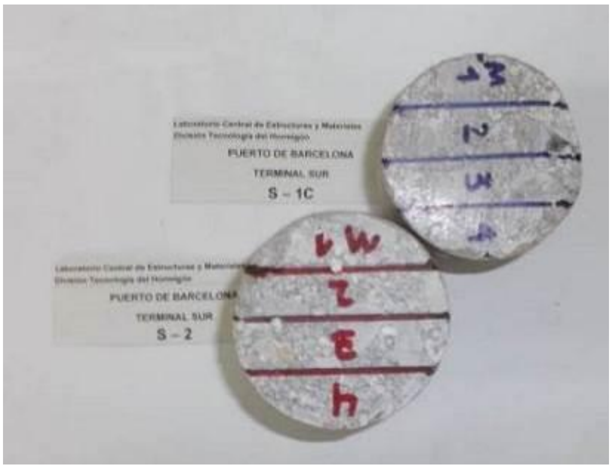


Figure 21. Permeability of concrete. Comparison of UPPER and LOWER concrete

All the results comply with the 50 mm maximum penetration required for the XS2 environment. In the caissons from Tenerife, where the concrete is classified as IIIc (equivalent to XS3), the maximum penetration depth should be 30 mm, a result that one of the two caissons does not reach. However, when comparing the results of the upper and lower zones, remarkably similar water penetration depths are consistently observed, showing that the permeabilities in both zones are very similar and that **the permeability of the concrete does not depend on the time that elapsed before the concrete came into contact with seawater.**

3.2 RESISTANCE OF CONCRETE TO CHLORIDE INGRESS

Concrete slices parallel to the face of the caisson exposed to the seawater were tested [12] to obtain chloride penetration profiles at the upper and lower zones of each core (Photograph 11).



Photograph 11. Preparation of samples for the chloride profile

The extracted cores of concrete are located behind the caisson reinforcement; hence, the profiles obtained start approximatively between seven and ten centimetres from the outer face, depending on the caisson tested. Figure 22 shows the results from Barcelona, and Figure 23 shows the results from Granadilla (Tenerife).

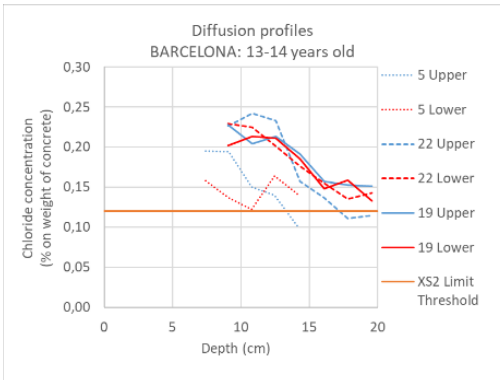


Figure 22. Chloride diffusion profiles. Caissons from Barcelona Harbour. Comparison of UPPER and LOWER concrete

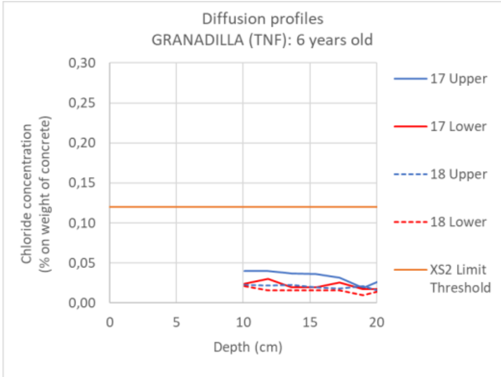


Figure 23. Chloride diffusion profiles. Caissons from Tenerife Harbour. Comparison of UPPER and LOWER concrete

The three caissons evaluated in Barcelona Port (Figure 22) do not show significant differences in the chloride profiles measured in the upper and lower zones of each core. Therefore, the results obtained show that **the fact of being in contact with seawater after construction (lower zone) did not cause the concrete to react to chlorides differently in the long term.**

In addition, Figure 22 also shows how, after 13 years of service, the chloride contents reached after reinforcement in Barcelona exceeded the chloride threshold proposed by the Structural Code for the initiation of corrosion in a submerged marine environment (0.8% chlorides by weight of cement). However, reinforcing bars were extracted from the core from caisson D (Barcelona), and they do not show active corrosion processes, as seen in Photograph 12.

Photograph 12. Vertical reinforcement without corrosion. Caisson D. Barcelona Port

The concrete around these bars had a chloride content, expressed by weight of cement, of 1.25% in the upper zone and 1.04% in the lower zone. Although these chloride contents are clearly higher than the 0.8% threshold set by the Structural Code, no corrosion processes were observed. For this reason, **the chloride content required to start a corrosion process in submerged concrete (XS2) must be greater than 1.25%** by weight of cement**,** and the theoretical service life of any concrete submerged in seawater (XS2 environment) must be higher than that provided for in the Spanish regulations, which establishes a conservative chloride threshold for the initiation of corrosion of 0.8% by weight of cement.

In the two Tenerife caissons evaluated, after six years of exposure to seawater, chlorides have not reached the depths tested in the upper nor the lower zones of the caisson. Therefore, the comparison between caisson heights only allows us to conclude that the initial chloride concentration is 0.14% by weight of cement, below the limit set by the Structural Code for reinforced concrete (0.2% by weight of cement).

3.3 PREVIOUS FIELD STUDIES ON THE DURABILITY OF FLOATING CAISSONS

Between 2004 and 2009, CEDEX carried out a study on docks constructed with floating caissons [7][18][19].

The seven docks studied and made with floating caissons were in good condition without evidence of corrosion pathologies, especially in those structures made using concretes with pozzolanic content (Photograph 13, Photograph 14, Photograph 15).

Photograph 13. Dock made with floating caissons in an XS3 environment, 2 years of service. Close-up of bars uncovered, with no signs of corrosion. BFS cement, 32,5-SR

Photograph 14. Dock made with floating caissons in an XS3 environment, 2 years of service. Close-up of bars uncovered, with no signs of corrosion. Pozzolanic cement, 32,5-SR/MR

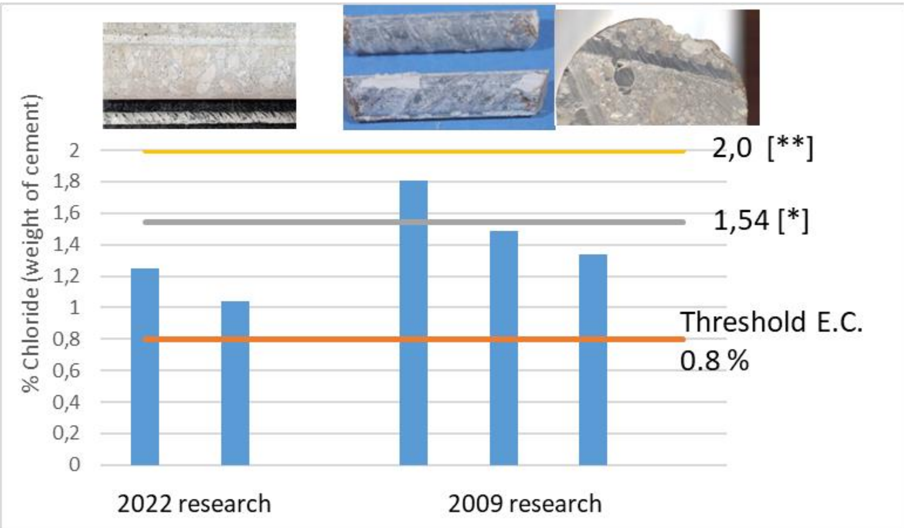
Photograph 15. Dock made with floating caissons in an XS3 environment, 31 years of service. Without signs of corrosion. Pozzolanic cement

Two docks made with caissons located in an XS2 environment (under seawater) in Barcelona and Valencia were studied. They were built with H-25 concrete with a water-binder ratio of 0.5 and were evaluated after 4.5 and 6.5 years of exposure to chlorides. As in the recent study (2022), specimens were extracted from the upper face of the dock to the concrete of the caissons that is always in a submerged marine environment (XS2 zone).

Photograph 16 Extraction of specimens in Valencia Port

Photograph 17. Extraction of specimens in Barcelona Port

The study of the caissons in these two ports showed that, as in this study, there were bars with chloride contents above the threshold of 0.8% by cement weight that did not show any evidence of corrosion. Figure 24 shows the chloride concentration of all the bars without corrosion extracted from the submerged zone of different floating caissons analysed at CEDEX.



[*] Threshold for concrete in an XS2 environment. [20]

[**] Threshold for ordinary Portland concrete in an XS2 environment. [21]

Figure 24. Chloride percentage by weight of cement in submerged reinforcements without signs of corrosion. CEDEX studies 2009 and 2022

The results obtained at CEDEX are in accordance with other higher thresholds reported in the literature for the initiation of corrosion in submerged concrete, which are also shown in the figure. Therefore, **it can be concluded that the chloride threshold for the onset of corrosion proposed in the Spanish standard for submerged concrete** (0.8% by weight of cement) is conservative, and any evaluations carried out using this parameter will always be on the safe side, with estimates of the useful life of submerged concrete being somewhat lower than the reality.

Moreover, the fact that the chloride threshold for the initiation of corrosion in submerged concrete is higher than 1.50% by weight of cement further reduces the importance of seawater curing for the service life of concrete in an XS2 environment. In other words, in terms of the durability of the floating caissons, the higher the quantity of chlorides needed to initiate corrosion in the reinforcements, the less relevant the fact that the chloride front has advanced a few millimetres further because the concrete was cured in seawater during the structure's first days of life.

In addition to the two submerged concrete docks described above, previous CEDEX studies evaluated the tidal zone of five docks made with floating caissons. Two of the conclusions reached in this 2009 research are relevant to this study on concrete curing in floating caissons:

- **The selection of the type of cement**: in 2009, it was found that the use of cements with a high content of pozzolanic additions (fly-ash and slag) made it possible to obtain very low chloride penetrations in the floating caissons studied, even with more lax regulations than those currently in force, as shown in Figure 25.

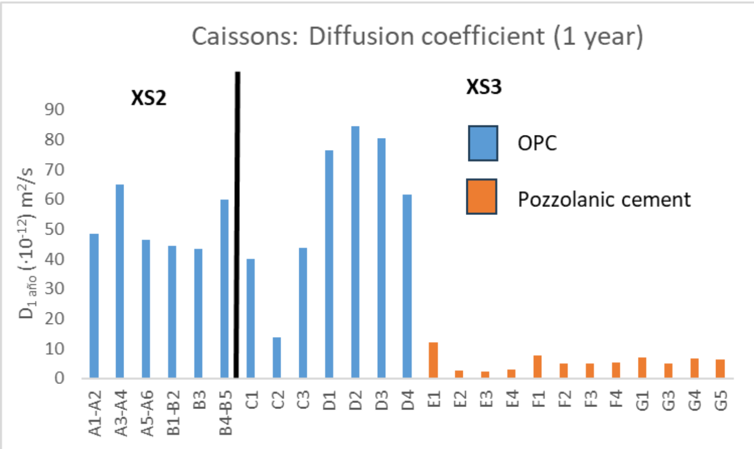


Figure 25. Diffusion coefficients at 1 year for the different caissons studied

This statement agrees with the statement made following the laboratory study to evaluate the effect of seawater curing on reinforced concrete in submerged marine environments: **the proper selection of the binder is more important than the type of curing carried out.**

- **Properly executed and cured tidal zone:** This study showed that the area of the caisson with the highest durability requirements is the tidal and splash zone (XS3), as the threshold for corrosion initiation decreases due to the higher availability of oxygen for the reinforcement to corrode.

  It is important to note that this area of the caisson does not come into premature contact with seawater as it remains surfaced until the moment of anchoring. Even so, after the final removal of the formwork, it would be highly advisable to continue with the freshwater curing of the non-submerged area to optimise its finished quality, as this is the area of the caisson that will be subjected to the most aggressive marine environment while in service (splashing and tidal movements, XS3).

4 CONCLUSIONS

The results obtained in the field and laboratory studies lead to the conclusion that there is no significant risk of increased steel reinforcement corrosion due to the construction process of the caissons on the floating platform, according to the conclusions summarized below:

- The laboratory and on-site results show that premature contact with seawater influences neither the compressive strength nor the permeability or porosity of concrete.
- The laboratory research has proved that **the proper selection of the binder is more important than the curing method carried out**. Chloride penetration is much higher in OPC than in cements with more than 21% of fly ash or more than 66% of blast-furnace slag, whether cured with fresh water or not. The research on real caissons made with pozzolanic additions confirms their influence on the durability of these structures.
- The laboratory results have also shown that from an early age the blast-furnace slag concrete performs particularly well, regardless of the type of curing. The fly ash concrete initially performs worse against chlorides when cured with seawater but as time progresses, the results converge and the depth of chloride penetration in both seawater and freshwater cured FA concrete is very similar. Finally, **the Portland cement concrete is the worst performing of the three when seawater cured, regardless of its age, with a difference in chloride depth of about 10 mm.**
- The research on real caissons demonstrated that being in contact with seawater after construction did not alter chloride resistance in the long term. Also notable is the finding that keeping concrete under seawater (XS2 environment) increases the chloride threshold for the initiation of corrosion up to 1.5 % by weight of cement, minimising the importance of the fact that the chloride front has advanced a few millimetres further due to curing the concrete in seawater.

Taking into account the results obtained in the present study, **meeting the mix design and permeability requirements of the Structural Code for XS3 environment** (cement content ≥350 kg/m3, w/c≤ 0,45 and maximum water penetration depth ≤ 30 mm) **would be sufficient** to ensure that the corrosion durability of the floating caissons is not diminished by the early immersion of the concrete that will definitely remain under seawater**, provided that it is used as a binder: CEM II/B-V, CEM II/A-D, CEM III/A, CEM IIIB, concretes with more than 6% silica fume or 20% fly ash, as well as CEM IV that gives the concrete this same pozzolanic addition content.**

If it is not possible to use the cements described above, increasing the coating by 10 mm will ensure that the concrete of the floating caissons will have a performance against chlorides at least equivalent to that of the same concrete previously cured with fresh water, provided that the permeability and mix design requirements of the Structural Code for XS3 environment are maintained. To use other less demanding mix designs, a specific experimental study will be required.

Finally, it is important to remember the importance of **avoiding drying in the strip of concrete under the sliding formwork until the moment it is immersed in seawater**. The concrete immersion process after its manufacture must be carried out without allowing the concrete to dry at any time, to avoid further penetration of chlorides due to the absorption of seawater.

In a similar vein, the upper part of the caisson will remain surfaced without contact with seawater until the moment of anchoring, so it would be advisable to continue with the freshwater curing of this area after the formwork is removed to optimise its finished quality, as this is the area that will be subjected to the most aggressive marine environment (XS3), and is, therefore, the most critical area of the caisson from a durability point of view.

5 PREVIOUS PUBLICATIONS

Part of the work included in this document has been previously published in the paper entitled "Influence of seawater curing on reinforced concrete located in an XS2 environment" in the publication "*Proceedings of the fib Symposium 2023. Building for the Future: Durable, Sustainable, Resilient*", published by Springer. This publication extends the information already published, with further description of the materials tested, new results after four and a half years of exposure, capillarity and porosity tests, evaluation of the chloride threshold for the onset of corrosion in an XS2 environment and durability studies in caissons at seven Spanish ports.

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