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Impact of repairs on embodied carbon expenditure for a Reinforced Concrete Quay

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Notations:

LCA – life cycle analysis

ECO2 - indicative embodied CO_2

GGBS – ground granulated blast furnace slag

CEMI – Portland cement type I

AACI - Added Admixture Corrosion Inhibitor

MCI - Migration Corrosion Inhibitor

RC - Reinforced Concrete

t_i (years) - time until steel depassivation

R_{C65} ((kg/m^3)/(m^2/year)) - carbonation resistance obtained from laboratory results through an accelerated process with a carbon dioxide concentration of 90×10^{-3} kg/m^3

k_0 - Test parameter

k_1 - Rel. humidity parameter

k_2 - Cure parameter are the parameters that account, respectively, for: test type; relative humidity and cure

t_0 - reference period =1 year

n - factor that considers the influence of soaking/drying over time.

c - concrete cover

erf - error function

C_R - chloride threshold by cement weight (%)

C_s - surface chloride amount by cement weight (%)

C_i - initial chloride amount in the concrete mass by cement weight (%)

$K_{D,T}$ - Temperature parameter

$K_{D,H}$ - Rel. humidity parameter

$K_{D,C}$ - Cure parameter

k - product of the parameters $K_{D,C}$, $K_{D,RH}$, $K_{D,T}$

t_p (years) - propagation period

ϕ_0 (mm) - initial diameter of steel reinforcement

α - type of corrosion – uniform or pitting

i_{corr} - corrosion current density ($\mu A/cm^2$)

f_{td} - the tensile concrete cover strength

ϕ_0 - Steel bar diameter

C_R - chloride threshold

C_s - Chloride surface amount

t_L - design service life

t_g - predicted working life

P_f - probability of failure

Ce_i - embodied carbon expenditure for the i^{th} maintenance intervention ($kg.CO_2e/(kg/m^2)$)

n - number of interventions for an arbitrary value of 100 years

Abstract

Studies on structural repair using Life Cycle Analysis (LCA) are still lacking the environmental impact of repair actions. This research work shows that the choice of the best repair option for reinforced concrete (RC) structures is a function of long-term environmental impact, considering longevity of maintenance intervention and embodied carbon expenditure. The purpose of this work was to assess the lifetime of a quay superstructure exposed to an aggressive marine microenvironment using a probabilistic performance-based approach and to then select the best repair option for its RC structures. The comparison is made for RC service life using three different concrete types and two different corrosion inhibitors. Longevity and embodied carbon were predicted for the expected number of repair actions per each 100 years. It is shown that concretes may have a higher impact at the outset although resulting in a much lower impact across the service life of the structure.

Keywords: concrete durability; service life; marine environment; performance-based design; embodied carbon; LCA.

1. Introduction

One sixth of the world's CO_2 emissions arise from producing steel and cement, which are made efficiently, although used inefficiently, particularly in construction. In reinforced concrete (RC) structures, where concrete is the most widely used material in construction, one of the main strategies used so far to reduce carbon emissions is the partial replacement of clinker with industry by-products. The use of classic additions, considered as supplementary cementitious materials (Lothenbach et al., 2011), such as: limestone filler; blast furnace slag; fly ash; or silica fume, has been standard practice for decades since these supplementary cementitious materials gave different properties to the concrete making it adjustable to different environments, namely those where chemical action on concrete is considered aggressive (Coutinho and Gonçalves, 1994).

To achieve the goal of reducing CO_2 emissions of RC structures, a life cycle analysis (LCA) approach is required to quantify the potential environmental impact of a product or a service, according to standards ISO 14040:2006 (ISO 14040:2006) and ISO 14044:2006 (ISO 14044:2006).

One of the potential environmental impact of RC structures is associated with the embodied carbon and the mix component CEM I is responsible for the majority of the embodied carbon content found in concrete. Table 1 presents the embodied carbon contents for main constituents of reinforced concrete.

Table 1 - Embodied carbon contents for main constituents of reinforced concrete (based on SIMAPRO) (SIMAPRO, 2016) and on (Bath Inventory of Carbon and Energy (ICE), 2011); King D (2012).

Main constituents of RC	Embodied carbon eq. (kg CO2e /tonne)
CEM I	950
GGBS	52
Fly ash	4
Limestone fines	32
Silica fume powder	28
Minor additional constituent	32
Aggregate	5
Reinforcement	427

Based on UK information, indicative embodied CO_2 (ECO2) figures for CEM I, GGBS and fly ash are derived using data from (SIMAPRO, 2016) and on Bath Inventory of Carbon and Energy (Bath Inventory of Carbon and Energy (ICE), 2011) and are "cradle-to-gate" values, not including the transport from place of manufacture to concrete plants.

The CO_2 emissions associated with the mixing, transfer and storage of silica fume slurry are 14 kg per tonne of slurry, from the production site in Norway to the port in the UK (Elkem/Enviros), which equates to 28 kg per tonne of silica fume powder (according to (King D (2012))).

Structures use larger quantities of materials and systems and their service life must be at least 50 or 100 years. The selection of the optimum repair material/system such as a proper concrete composition, increases LCA impact and relevance when it is correlated to the durability of the structure. Here, the effectiveness of a low carbon project should be judged by its expected service life together with embodied carbon and energy expenditure (Brás A, 2016), (HM Government, 2010), (Adalberth K.,1997), (de Wilde P, 2014), (Thomas et al, 2017).

Studies on structural repair using LCA are and have been limited still to the environmental impact of repair actions.

From a structural repair and maintenance perspective, the environmental and economic impact of each possible solution must be evaluated.. Early structural deterioration associated with lack of regular maintenance can widely reduce the value of these existing assets. In fact, one material may have a higher impact at the outset but result in a much lower impact across the structure service life.

2. Structural repair solutions - service life and carbon expenditure

2.1 Case study characterisation

Repairs with high life expectancy are of low carbon impact and are "green" maintenance types, since the cumulative effect of "non-green" maintenance increases the total embodied carbon expended far more quickly than "green" maintenance and does not attain the same required longevity (Kayan B et al, 2016).

There are several examples of structures (quay, bridges, ports floating dikes, etc) where the choice of a repair solution led to the consumption of tonnes of RC. This substantial RC consumption does not bring significant benefits from a service life perspective, enhancing the short and long-term environmental impact (Rosa P, 2014)); (Holmes N, 2009); (Pearson-Kirk D., 2009); (Pearson-Kirk D., 2009b).

One example is the Mitrena Yard, a Portuguese quay built in 1973 in Seubal to cope with increased demand; both for ship repair and shipbuilding. The structure presented high level of corrosion due to an aggressive marine microenvironment with chlorides and still in progress and in 2000 the structure was repaired. However, currently the quay is only 15 years old yet has suffered severe issues with corrosion. It was therefore necessary to undertake/recommend repair actions to address the corrosion (Figures 1 and 2).

Figure 1 - View of the Quay 3.

Figure 2 - View of the Mitrena Yard.

In order to preserve, replace and repair all structural elements - Quay 3 and Duque d'Alba platform (Figures 3-5), a study was proposed to compare the RC service life using two different corrosion inhibitors and three different concrete types possible of implementing on site. The corrosion inhibitors were Added Admixture Corrosion Inhibitor, MCI 2005 ® – AACI - and a surface applied Migration Corrosion Inhibitor, MCI 2020 ® - MCI, (both inhibitors from Cortec/ Quimilock) and the three different concrete types were CEM I, CEM II/ A-D and CEM IV/B.

This research work intends to demonstrate that the most suitable repair option for RC structures should be considered as a function of the long-term environmental impact. In particular, this should consider the longevity of maintenance intervention and the embodied carbon expenditure. The purpose was to assess the improvement of the lifetime of the quay superstructure exposed to an aggressive marine microenvironment using a probabilistic performance-based approach and select the best repair option for the RC structures.

The design for durability performance took into account the following:

- the intended working life of the structures must be 100 years;

- the maximum acceptable probability of reaching the steel reinforcement corrosion could not be higher that 2.3%, according to Eurocode 0 specifications for a reliability class RC3.

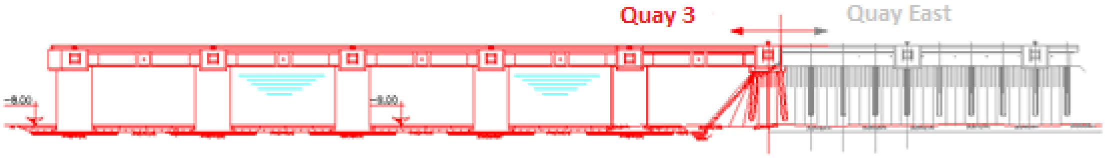

Figure 3 - Longitudinal view of the Quay 3.

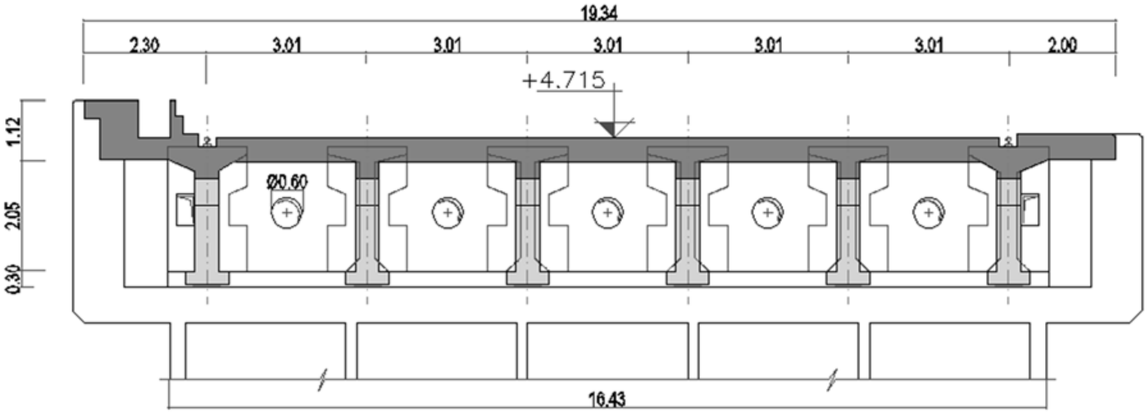

Figure 4 - Transversal view of the Quay 3.

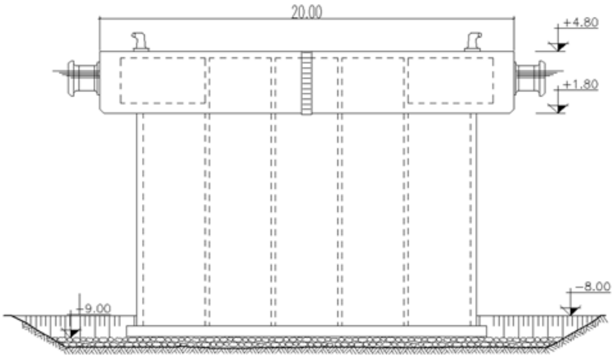

Figure 5 - View of the Duque d'Alba platform.

2.2. Corrosion inhibitors for concrete elements

Nowadays, state-of-the-art related to durability design approaches of RC structures includes techniques that can be either alternative or supplementary to traditional repair (Duracrete, 2000; CS TR61, 2004; NP EN 206-1, 2005; fib, 2006; fib, 2010; ISO 1620, 2012). The corrosion of steel reinforcement is the main cause of deterioration of these structures and depends on the surrounding environment. The environmental agents that take part in corrosion are carbon dioxide (CO_2) and chloride ions (Cl^-).

Corrosion inhibitors can be used as a repair measure or can be included in new concrete compositions. They are classified by Söylev and Richardson (2008) according to their specific action: anodic inhibitors; cathodic inhibitors and mixed inhibitors. Besides this, corrosion inhibitors for the repair of RC structures can be used in two different ways:

- combined with traditional repair techniques, allowing a multi-barrier strategy, added as an admixture to fresh concrete (hereafter designated AACI), or applied on repaired hardened concrete surfaces, acting as a migrating corrosion inhibitor (hereafter designated MCI) or;
- as a sole measure, applied on hardened existing concrete surfaces, acting as a migrating corrosion inhibitor (MCI).

Currently, the main property of these agents is to act in the propagation period (t_p), i.e., when corrosion starts. Some of these corrosion inhibitors also have the ability to act as pore blockers, acting in the initiation period (t_i). Therefore, it is important to clarify the environmental exposure classes established by the European standards (EN 1992-1-1 2004; EN 206-1, 2005), where corrosion is the main cause of deterioration of RC structures.

Based on the location of the Mitrena quay, the performance of concrete was quantified in terms of service life, as regards corrosion of steel reinforcement, with and without the presence of corrosion inhibitors (Table 2) in four different microenvironments: XC3, XC4 and XS1 and XS3 environmental exposure classes.

Table 2 – Definition of corrosion environmental exposure classes: EN 206-1 (2005) and EN 1992-1-1 (2004)

Environment type	European Equivalent classes	Description of the environmental exposure classes
Carbonation	XC4	High humidity on a cyclic basis or concrete surfaces subject to water contact
	XC3	Moderately humid.
Chlorides	XS1	Areas exposed to airborne salt but not in direct contact with sea water.
	XS3	Tidal, splash and spray zones.

3. Experimental and modelling tests on the durability of the concrete elements

The option to solve the steel reinforcement corrosion problem was based on the need for removing partially or totally the Reinforced Concrete (RC) elements (Figures 6 and 7), especially the contaminated concrete around the outer rebars and replacing it with new and protected concrete.

For different environmental classes, a group of different modelling tests to be applied to the concrete elements of the structure was defined.. The option was to evaluate the performance of corrosion inhibitors through a performance-based method using probabilistic calculus of service life of reinforced concrete structures.

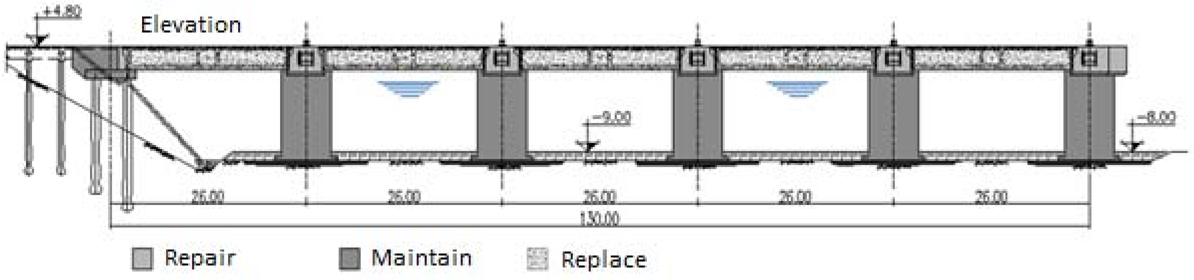

Figure 6 - Longitudinal view of the Quay 3 - exposure classes associated with microenvironments in Quay 3: XS1 and XS3; XC3 and XC4.

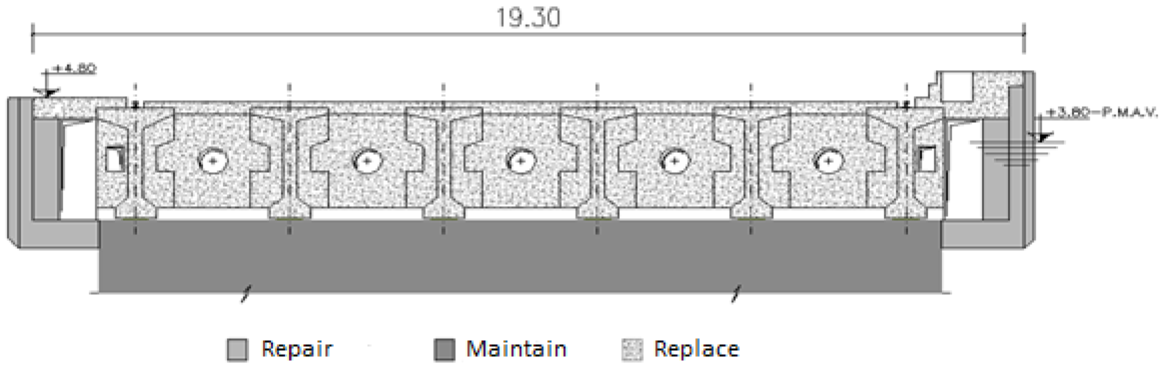

Figure 7 - Transversal view of the Quay 3 -exposure classes associated with microenvironments in Quay 3: XS1 and XS3; XC3 and XC4.

The first step was to manufacture 4 different concrete mixes in the laboratory to simulate the existing concrete characteristics that could be adopted in the repair situation (Table 3). The compressive strength and the durability properties of those 4 concrete mixes were studied as regards to accelerated diffusion of CO_2 and rapid chloride migration together with available results of the performance of two specific types of corrosion inhibitors: MCI 2005 ® -which is an Added Admixture Corrosion Inhibitor (AACI) and MCI 2020 ® - which is a Surface applied Migration Corrosion Inhibitor (MCI) from Cortec/Quimilock company.

Each concrete composition included cements designed in accordance with EN 197-1 (2000). The cement (binder) types used in the four concrete compositions studied, as well as the cement dosage and w/c ratio are shown in Table 3.

<u>Carbonation tests:</u> samples with 100 mm diameter and 50 mm of thickness were subjected to an environment with 65% RH, 20 ºC and 5% of CO_2 air content for 14, 28, 42 and 56 days after a 28 days conditioning: 3 days curing in saturated environment and 25 days in 65% RH and 20 ºC (LNEC E391, 1993).

<u>Chloride migration tests:</u> the experimental procedure for the determination of the coefficient of migration followed the rapid non-steady state chloride test (NT Build 492, 1999), which included cylindrical specimens with 100 mm diameter and 50 mm of thickness. The specimens were subjected to 14 days of drying at 20ºC and 50% of RH before being in a low pressure hermetic recipient and immersed in a solution of calcium hydroxide for vacuum treatment.

Table 3 – Concrete compositions tested and results at the age of 28 days.

Cement (binder) type	Constituents	Dosage kg/m^3	w/c	f_{cm}[1] MPa	R_{C65}[2] $(kg/m^3)/(m^2/yr)$	D_0[3] m^2/s	n[4]
CEM I (OPC) – original situation	>95% clinker	320	0.53	56.1	100	-	-
CEM II/A-D	8% SF; >95% clinker	320	0.48	41.1	-	XS1: 5.1×10^{-12} / XS3: 2.0×10^{-12}	0.55
CEM IV/B	40% FA; >55% clinker	340	0.45	52.1	47	XS1: 14×10^{-12} / XS3: 6.5×10^{-12}	0.65

SF – silica fume; FA – fly ash

[1] Mean cubic compressive strength. Molds with 150 mm edge tested following EN 12390-1 (2009)

[2] Carbonation resistance

[3] Migration Coefficient for XS1 and XS3

[4] Ageing factor

Three scenarios were then defined for each concrete composition: i) plain concrete; ii) concrete with added admixture inhibitor and iii) concrete with a surface applied migration inhibitor.

The corresponding design lifetime calculations were then undertaken using the probabilistic approach, where the mathematical models, parameters and assumptions for the computation of lifetime are based on the Portuguese specification LNEC E465 (2009) as the national annex to NP EN 206-1 (2005) and (Tuutti K, 1982). The probabilistic estimate of the design lifetime is carried out by the Monte Carlo method. The performance level depends on the Action (S), such as CO_2 and Cl^-, and on the Resistance (R) such as the concrete cover and concrete properties. The measure of risk associated with the specific event of $R(t) < S(t)$ can be expressed as the probability of failure. Figure 8 presents the lifetime design approach using probabilistic methods.

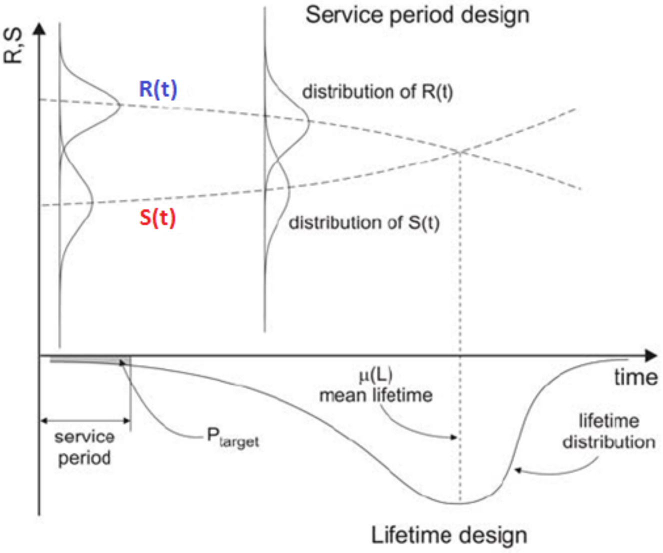

Figure 8 - Lifetime design using probabilistic methods.

The modelling of the initiation period for carbonation corresponds to the study of CO_2 penetration into concrete and the diffusion process and is based on Fick's 1st law for the estimation of the carbonation depth over time, according to LNEC E465 (2009) (Eq. (1)):

$$t_i = \left[\frac{R_{C65}\ c^2}{1.4 \times 10^{-3}\ k_0\ k_1\ k_2\ t_0^{\ 2n}} \right]^{\frac{1}{1-2n}} \tag{1}$$

where t_i (years) is the time until steel depassivation, c (mm) is the concrete cover of steel reinforcement, R_{C65} ((kg/m^3)/(m^2/year)) is the carbonation resistance obtained from laboratory results through an accelerated process with a carbon dioxide concentration of 90x10^{-3} kg/m^3, k_0, k_1 and k_2 are the parameters that account, respectively, for: test type; relative humidity; and cure. t_0 is the reference period =1 year and the parameter n is the factor that considers the influence of soaking/drying over time.

Within the same procedure, the initiation period resulting from chlorides action is defined by LNEC E465 (2009) following the recommendations of fib bulletin 34 (2006). The initiation period is expressed by Eq. (2).

$$t_i = \left[\left(\frac{2}{c}\, erf^{-1}\left(1 - \frac{C_R - C_i}{Cs - C_i} \right) \right)^{-2} \frac{1}{k\ D_0\ t_0^{\ n}} \right]^{\frac{1}{1-n}} \tag{2}$$

where c is the concrete cover, *erf* is the error function, C_R the chloride threshold by cement weight (%), C_s the surface chloride amount by cement weight (%), C_i the initial chloride amount in the concrete mass by cement weight (%), k the product of the parameters that consider cure ($K_{D,C}$), relative humidity ($K_{D,RH}$) and temperature ($K_{D,T}$) and n the ageing factor.

The equation and variables for the estimation of the propagation period in chloride environments are the same as for carbonation exposure classes and presented below – Eq (3). However, it is worth mentioning that in chloride environments the development of pitting corrosion is common, which is non-uniform and more intensive and concentrated at different spots of steel cross-section. The propagation period is based on Faraday's law resulting in Eq. (3) where the radius reduction factor of the steel reinforcement is obtain from the empirical equation (Eq. (4)).

$$t_p = y\, \phi_0 \, \frac{1}{1.15\, \alpha\, i_{corr}} \tag{3}$$

where t_p (years) is the propagation period, ϕ_0 (mm) is initial diameter of steel reinforcement, α the type of corrosion – uniform or pitting – and i_{corr} (μA/cm^2) the corrosion current density (μA/cm^2).

For carbonation induced corrosion it is considered that corrosion is uniform and therefore E465 (2009) establishes α=2. For chlorides environments α=10 to take into account the pitting corrosion. The radius reduction factor y (mm) is then expressed as:

$$y = \left(74.5 + 7.3\, \frac{c}{\phi_0} - 17.4\, f_{td} \right) \frac{0.2}{\phi_0} \tag{4}$$

where f_{td} is the tensile concrete cover strength.

All the parameters that represent the variables of the equations are defined according to the Portuguese standards which include specifications E464 (2009) and E465 (2009).

The experimental results obtained by Andrade (2012), show the effect of the corrosion inhibitor in the propagation period t_p, by means of i_{corr} reduction, as it is also possible to account for an additional effect in the initiation period t_i through the increase of the chloride threshold C_R (Table 43).

Table 4 – Experimental results of corrosion inhibitor admixtures tested by Andrade (2012) (Report requested by Quimilock, S.A.)

Inhibitor admixture type Commercial designation	Inhibitor admixture Type and Proportion	Increase* in chloride threshold – C_R	Reduction* of corrosion velocity - i_{corr}
Mixed inhibitors Aminocarboxylates MCI 2005 ®	Added Admixture Corrosion Inhibitor AACI (0.60 l/m³ concrete volume)	54%	83%
Mixed inhibitors Aminocarboxylates MCI 2020 ®	Surface applied Migration Corrosion Inhibitor MCI (0.27 l/m² concrete surface)	72%	46%

*in comparison with the reference concrete mix of the report by Andrade (2012).

Since Design service life (t_L) of an RC structure is the sum of t_i and t_p, t_L must present higher values than the predicted working life (t_g) that was decided to adopt for the Mitrena quay: 100 years.

Therefore, the carbonation modelling of design service life is defined according to the following expression:

$$g(x) = t_L - t_g = \lambda \left\{ \left[\frac{R_{C65}\, c^2}{1.4 \times 10^{-3}\, k_0\, k_1\, k_2\, {t_0}^{2n}} \right]^{\frac{1}{1-2n}} + \frac{y\, \phi_0}{1.15\, \alpha\, I_{corr}} \right\} - t_g \qquad (5)$$

and chloride modelling of design service life is:

$$g(x) = t_L - t_g = \lambda \left\{ \left[\left(\frac{2}{c} erf^{-1} \left(1 - \frac{C_R - C_i}{C_S - C_i} \right) \right)^{-2} \frac{1}{k\, D_0\, t_0^n} \right]^{\frac{1}{1-n}} + \frac{y\, \phi_0}{1.15\, \alpha\, I_{corr}} \right\} - t_g \qquad (6)$$

The probability of failure corresponds to the probability that the limit state function is negative:

$$P_f = P[g(x) < 0]$$

4. Correlation between carbon expenditure and service life of the structure

4.1 Probabilistic calculus of service life

The implementation of Service Life modelling adopted the predicted design specifications for concrete cover as well as the variables for each studied scenario (XC3, XC4, and XS1, XS3), as regards the use of inhibitors. The effect of the inhibitors is quantified by changing the value of the corrosion current density i_{corr} in both carbonation and chloride environments, and the chloride threshold C_R in the chloride environment. All corresponding variables are presented in Tables 5-8.

Table 5 – Carbonation class XC4 (exposed) – Calculus variables

Variables	Concrete		
	Plain	Corrosion Inhibitor (AACI)	Migrating Corrosion Inhibitor (MCI)
Cover, c (c_{nom})	40 mm	40 mm	40 mm
Test parameter, k_0	3	3	3
Rel. humidity parameter, k_1	0.41	0.41	0.41
Cure parameter, k_2	1	1	1
Wet/dry cycle parameter, n	0.085	0.085	0.085
Corrosion current density, i_{corr}	1.0 μA/cm^2	0.17 μA/cm^2	0.54 μA/cm^2
Tensile strength, f_{td}	2 MPa	2 MPa	2 MPa
Steel bar diameter, ϕ_0	8 mm	8 mm	8 mm

$i_{corr(AACI)}$ = (1-0.83) $i_{corr\ (plain)}$ = 0.17 $i_{corr\ (plain)}$

$i_{corr(MCI)}$ = (1-0.46) $i_{corr\ (plain)}$ = 0.54 $i_{corr\ (plain)}$

Table 6 – Carbonation class XC3 (protected) – Calculus variables

Variables	Concrete		
	Plain	Corrosion Inhibitor(AACI)	Migrating Corrosion Inhibitor (MCI)
Cover, c (c_{nom})	35 mm	35 mm	35 mm
Test parameter, k_0	3	3	3
Rel. humidity parameter, k_1	0.77	0.77	0.77
Cure parameter, k_2	1	1	1
Wet/dry cycle parameter, n	0.02	0.02	0.02

Corrosion current density, i_{corr}	0.10 μA/cm^2	0.017 μA/cm^2	0.054 μA/cm^2
Tensile strength, f_{td}	2 MPa	2 MPa	2 MPa
Steel bar diameter, ϕ_0	8 mm	8 mm	8 mm

Table 7 – Chlorides class XS1(aerial) – Calculus variables

Variables	Concrete		
	Plain	Corrosion Inhibitor (AACI)	Migrating Corrosion Inhibitor (MCI)
Cover, c (c_{nom})	45 mm	45 mm	45 mm
Testing age, t_0	28 days	28 days	28 days
Chloride threshold, C_R	0.4% (binder wt)	0.62% (binder wt)	0.69% (binder wt)
Chloride surface amount, C_s	2.4% (binder wt)	2.4% (binder wt)	2.4% (binder wt)
Temperature parameter $K_{D,T}$	0.8	0.8	0.8
Rel. humidity parameter $K_{D,H}$	0.4	0.4	0.4
Cure parameter $K_{D,C}$	2.4	2.4	2.4
Corrosion current density, i_{corr}	0.50 μA/cm^2	0.09 μA/cm^2	0.27 μA/cm^2
Tensile strength, f_{td}	3 MPa	3 MPa	3 MPa
Steel bar diameter, ϕ_0	8 mm	8 mm	8 mm

$C_{R(AACI)} = 1.54\ i_{corr\ (plain)}$
$C_{R(MCI)} = 1.72\ i_{corr\ (plain)}$
$i_{corr(AACI)} = (1\text{-}0.83)\ i_{corr\ (plain)} = 0.17\ i_{corr\ (plain)}$
$i_{corr(MCI)} = (1\text{-}0.46)\ i_{corr\ (plain)} = 0.54\ i_{corr\ (plain)}$

Table 8 – Chlorides class XS3 (tidal/splash) – Calculus variables

Variables	Concrete		
	Plain	Corrosion Inhibitor (AACI)	Migrating Corrosion Inhibitor (MCI)
Cover, c (c_{nom})	55 mm	55 mm	55 mm
Testing age, t_0	28 days	28 days	28 days
Chloride threshold, C_R	0.3% (binder wt)	0.46% (binder wt)	0.52% (binder wt)
Chloride surface amount, C_s	4.1% (binder wt)	4.1% (binder wt)	4.1% (binder wt)
Temperature parameter $K_{D,T}$	0.8	0.8	0.8
Rel. humidity parameter $K_{D,H}$	0.4	0.4	0.4
Cure parameter $K_{D,C}$	2.4	2.4	2.4
Corrosion current density, i_{corr}	1.0 μA/cm^2	0.17 μA/cm^2	0.54 μA/cm^2
Tensile strength, f_{td}	3 MPa	3 MPa	3 MPa
Steel bar diameter, ϕ_0	8 mm	8 mm	8 mm

The probabilistic analysis of service life distribution is carried out using the statistical parameters of the involved variables: mean values (Tables 5 to 8) and standard deviation with their distribution laws according to Faustino et al. (2014) and Rosa (2014). The implementation of the cited method was carried out by means of the Monte Carlo method with 1 000 000 generated values for each random variable.

Figures 9 and 10 present the design service life results where Pf reached 2.3%, where the proportion of both initiation and propagation periods is also expressed.

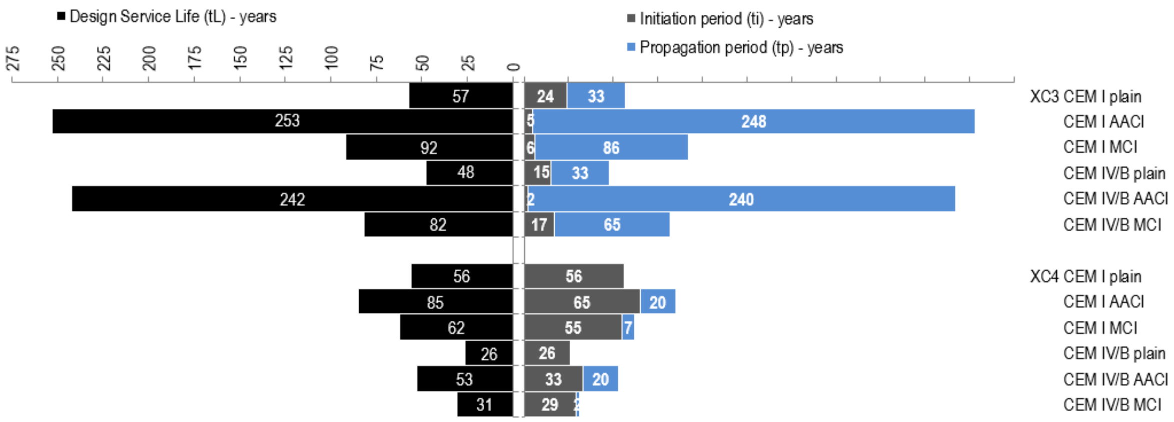

Figure 9 - Design Service Life t_L, initiation period t_i and propagation period t_p for the exposure classes XC3 (concrete cover=35 mm) and XC4 (concrete cover=40 mm).

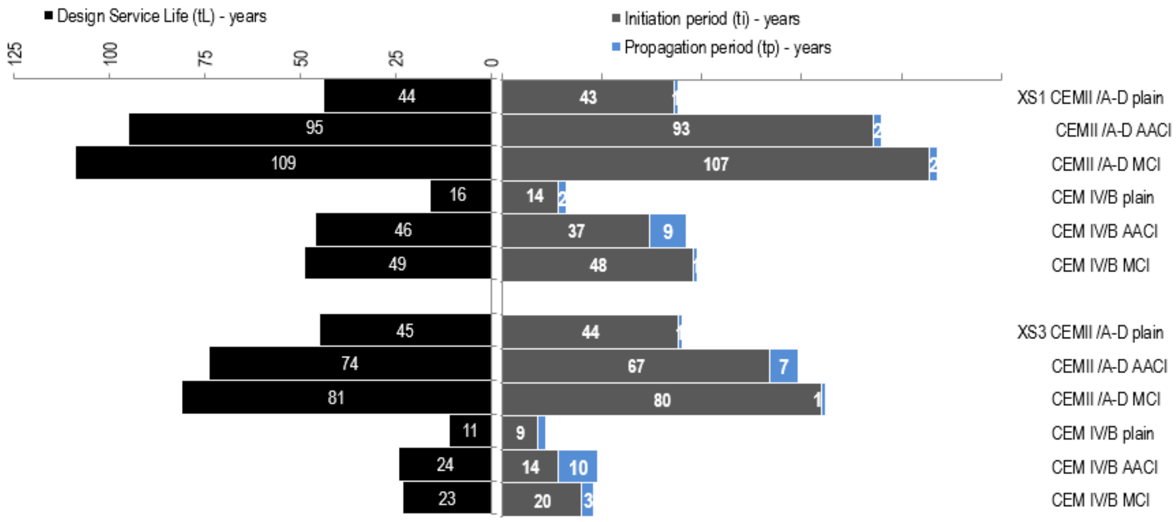

Figure 10 - Design Service Life t_L, initiation period t_i and propagation period t_p for the exposure classes XS1 (concrete cover=45 mm) and XS3 (concrete cover=55 mm).

Regarding carbonation (Fig. 9), AACI present enhanced performance when compared to plain concrete mixes or the ones with applied MCI. However, realistic service life values are not expected to exceed 100-120 years if up-to-date criteria are followed. Besides this, with regard to the application of AACI, its use is limited to traditional repair works, i.e., replacing of contaminated concrete mass. XC4 represents the most aggressive environment for the tested solutions and all solutions leads to reduced values of service life. Besides this, in XC4 environments, it is necessary to increase the concrete cover from 40 to 45 mm and test if it ensures a design service life higher than 100 years.

The results of chloride modelling (Fig. 10) show that with AACI the initiation period contributes the largest amount to the total design service life. However, considering the results for chloride environments (XS1 and XS3) and specially those of tidal/splash exposure (class XS3), the contribution of the propagation period is almost negligible and the design service life is less than 100 years in most situations, which was the intended working life of the structure defined by the owner (Lisnave).

Therefore, it was decided to analyse the effect of increasing the cover in the service life of concrete exposed to XC4 and XS3, particularly with regard to evaluating concretes with cement type CEM II/ A-D. The objective was to select the minimum cover to ensure a design service life higher than 100 years.

Figs. 11 and 12 present the design service life results where Pf reached 2.3%, for the exposure classes XC4 (concrete cover=45 and 50 mm) and XS3 (concrete cover=60 and 65 mm).

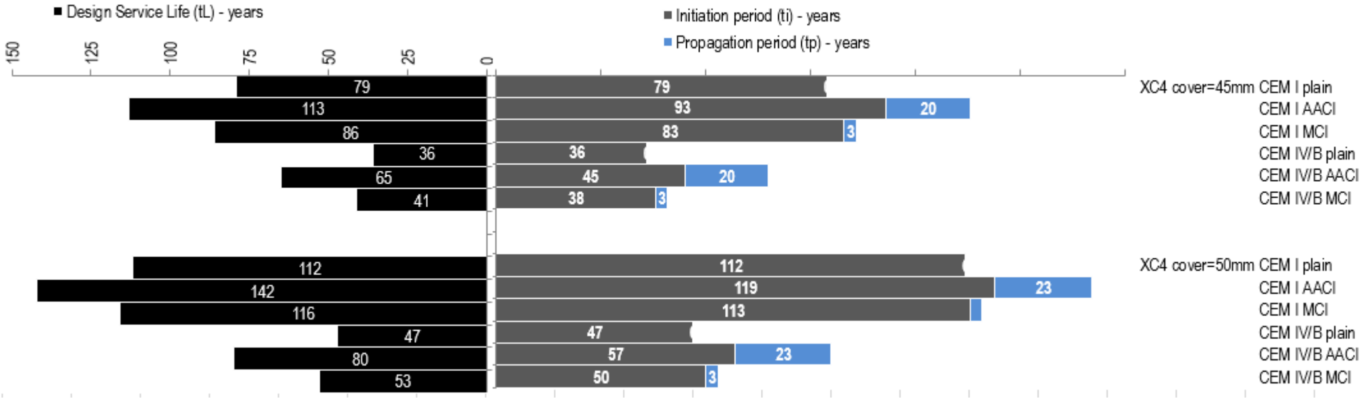

Figure 11 - Design Service Life t_L, initiation period t_i and propagation period t_p for the exposure classes XC4 (concrete cover=45 and 50 mm).

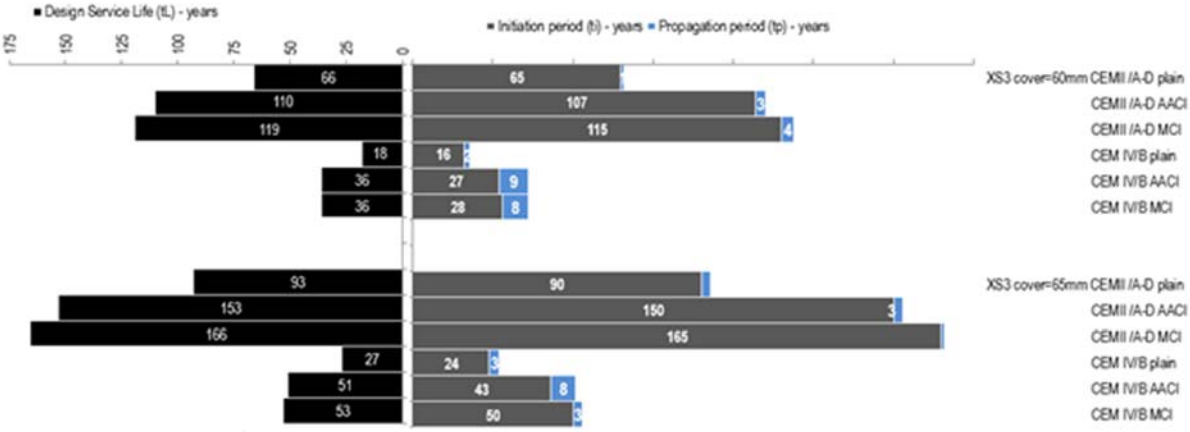

Figure 12 - Design Service Life t_L, initiation period t_i and propagation period t_p for the exposure classes XS3 (concrete cover=60 and 65 mm).

Fig. 11 shows that an increase in the concrete cover from 40 mm (Fig.9) to 45 mm is sufficient to ensure a design service life higher than 100 years if AACI is added to the OPC. Fig. 12 shows that increasing concrete cover has more impact than to add MCI or AACI. Nevertheless, CEMII / A-D is the best option for a concrete mix with a cover of 60 mm with AACI or MCI.

4.2. Embodied carbon expenditure

Each maintenance intervention is characterized by its longevity and embodied carbon. Repairs with low life expectancy have a high carbon impact and the cumulative effect of these types of maintenance actions increases the total embodied carbon expended whilst not attaining the required longevity. By multiplying the total repaired concrete cover by the embodied carbon expenditure for repairing 1m^3 of RC cover within a selected maintenance period, it is possible to obtain the cumulative embodied carbon expenditure (SUM Ce) (Eq. 6).

$$SUM\ Ce = \sum_i^n Ce_i \quad (7)$$

In eq. 7, n = number of interventions for an arbitrary value of 100 years, Ce_i = embodied carbon expenditure for the ith maintenance intervention (kg.CO$_2$e/(kg/m^2)) evaluated within selected “cradle-to-gate” boundary of LCA.

The reduction of RC service life increases maintenance actions needed due mainly to corrosion. Using LCA tools several environmental aspects of building materials could be quantified in the inventory analysis into some impact categories (Bath Inventory of Carbon and Energy (ICE), 2011); (SIMAPRO, 2016)). Concrete composition data (cement, aggregates and water) were modified from the Ecoinvent v.2.2 database, by switching into the Portuguese energy grid, as such processes were considered as sufficiently adherent to national practice. Table 9 presents, for each mortar, the expected Embodied Carbon expenditure for the all maintenance interventions (kg CO_2 equiv./ m^2) evaluated within selected “cradle-to-gate”.

Table 9 - Embodied carbon for each concrete composition used in each repair action.

Cement (binder) type	Composition	Embodied Carbon - Kg CO2e/Kg	Dosage kg/m^3	w/c
CEM I (OPC)	>95% clinker	0,19	320	0,53
CEM II/A-D	8% SF; >95% clinker	0,17	320	0,48
CEM IV/B	40% FA; >55% clinker	0,14	340	0,45

Figs. 9 and 11 show that for XC4 exposure classes, an increase of the concrete cover from 40 to 45 mm is enough to ensure a design service life higher than 100 years if AACI is added to the OPC. For XS3, Fig. 12 shows that CEMII / A-D is the best option for a concrete mix with a cover of 60 mm with AACI or MCI.

Based on those RC compositions, longevity and embodied carbon were predicted for the expected number of repair actions per each 100 years. Figures 13 and 14 show the design service life and the embodied carbon expenditure for the expected number of repair actions per each 100 years.

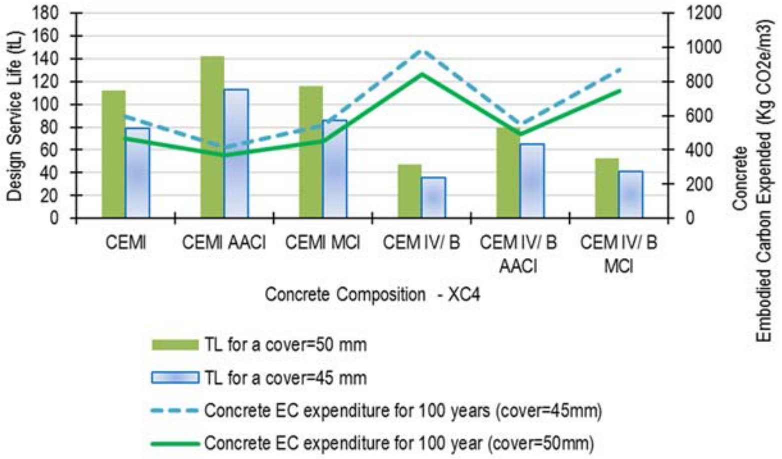

Figure 13 - Design service life (bars) and embodied carbon expenditure (lines) for each concrete composition used in each repair action - for the exposure classes XC4.

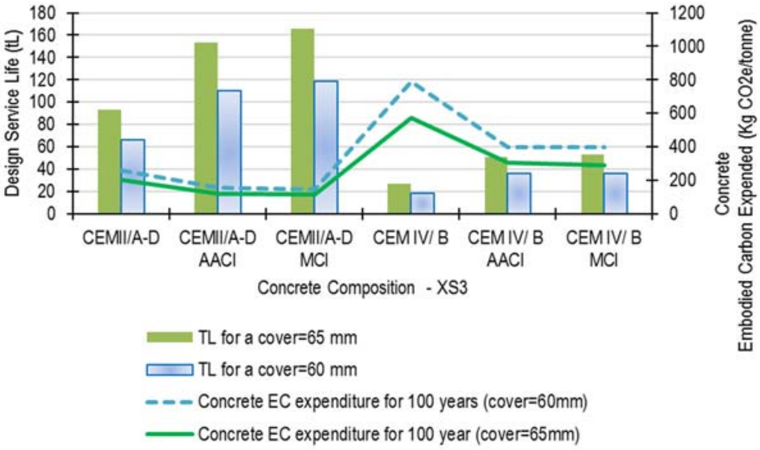

Figure 14 - Design service life (bars) and embodied carbon expenditure (lines) for each concrete composition used in each repair action - for the exposure classes XS3.

The previous results show that by increasing the RC service life, there is a decrease of embodied carbon expenditure. Nevertheless, the minimum value of embodied carbon expenditure could be associated with the maximisation of service life (see for example CEM I AACI - XC4) and/or eco-efficient changes in the concrete composition (CEM IV/B-AACI - XC4 and CEMII/A-D MCI - XS3).

It is shown that CEM IV/B plain concrete is the worst solution for service life and embodied carbon and, therefore, a substantial increase of repair actions and cumulative embodied carbon expenditure can be expected for this solution. Additionally, RC with AACI and CEM II/A-D reduces the embodied carbon of concrete repair actions by at least 3 times (even with an increase in concrete cover) in comparison to the other tested solutions.

5. Conclusions

A study was implemented to compare the RC service life using three different concrete types (CEM I, CEM II/ A-D, CEM IV/B) and two different corrosion inhibitors (AACI and MCI) to use on site. Then, based on these RC compositions, longevity and embodied carbon were predicted for the expected number of repair actions per each 100 years. This research work shows that the choice of the best repair option for RC structures is a function of the long-term environmental impact, considering the longevity of maintenance intervention and the embodied carbon expenditure. The purpose was to assess the improvement of the lifetime of the quay superstructure exposed to an aggressive marine microenvironment using a probabilistic performance-based approach to select the best repair option for the RC structures.

The modelling probabilistic, using experimental data, showed that cover thickness less than 60 mm is not recommended for XS3 exposure classes and that CEMII / A-D is the best option for a concrete mix with AACI or MCI.

In comparison with exposure class XC3, XC4 is the more aggressive environment and in this context an increase of the concrete cover from 40 to 45 mm is enough to ensure a design service life higher than 100 years if AACI is added to the CEM I concretes.

The results show that in environments where chloride contaminations are likely, the use of AACI shows outstanding improvement when compared with RC elements without any corrosion inhibitor (plain) or even with MCI in areas exposed to airborne salt but not in direct contact with sea water– class XS1. However, cover thicknesses less than 60 mm are not recommended for XS3 exposure classes. Here, CEMII / A-D is the best option for concrete mixes with cover of 60mm, is to include / add AACI or MCI to ensure that design service life exceeds 100 years.

By increasing the RC service life, there is a decrease of embodied carbon expenditure.

The minimum value of embodied carbon expenditure could be associated with the maximisation of service life (see for example CEM I AACI - XC4) and/or eco-efficient changes in the concrete composition (CEM IV/B-AACI - XC4 and CEMII/A-D MCI - XS3).

The work shows that CEM IV/B plain concrete is the worst solution in respect to service life and embodied carbon.

RC with AACI and CEM II/A-D is expected to reduce the embodied carbon of concrete repair actions by a factor of three (including for those cases with increased concrete cover) in comparison to other tested solutions.

The results show that by increasing the concrete cover there is also an increase of the RC service life and a decrease of embodied carbon expenditure, over the life of the asset.

It is demonstrated that concretes may have a higher environmental impact at the outset although resulting in a much lower impact across the service life of the structure.

Acknowledgments

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