Probabilistic Evaluation of the Sustainability of Maintenance Strategies for RC Structures Exposed to Chloride Ingress

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Abstract

Nowadays, multiple constraints imposed by economical, social and environmental considerations undergo maintenance planning optimization into a major challenge to designers, owners and users of infrastructure. This study presents a simplified methodology to evaluate the sustainability of maintenance strategies used in reinforced concrete structures exposed to chlorides. The proposed approach is illustrated throughout the paper with an application to large-scale maintenance of a real structure (*Agri-foodstuffs terminal wharf*). The repair strategy consists of demolition of the polluted concrete and rebuilding of cover by using three techniques (*wet shotcrete*, *dry shotcrete* and *formed concrete*). The repair times are estimated by taking the randomness of chloride ingress into account. Three criteria are used to evaluate the sustainability of the repair techniques: present value life-cost, waste production and CO_2 emissions. Based on this multi-criteria comparison, a simplified decision-making scheme based on a multi-objective index is proposed.

Keywords: reinforced concrete, sustainability, corrosion, maintenance, reliability.

1. Introduction

Chloride-induced corrosion affects significantly the operational life of reinforced concrete (RC) structures located close to the sea shore or in contact with de-icing salts. The mechanisms by which corrosion affects load carrying capacity of RC structures are: loss of reinforcement cross-section, loss of bond between steel and concrete, concrete cracking and RC delamination. RC structures are generally designed for a service life between 50 and 100 years. However, in chloride-contaminated environments many structures begin to deteriorate after 20 to 30 years (Kumar Mehta, 1997; Poupard et al., 2006; Rosquoët et al., 2006). Therefore, to guarantee optimum levels of serviceability and safety during the life-cycle, maintenance planning optimization becomes a major challenge with multiple constraints imposed by economical, social and environmental considerations.

Design, maintenance, repair and rehabilitation of construction projects are based mainly on feasibility benefit cost analysis. However, environmental requirements demand integrated design processes directed to: (1) optimize the management of resources; (2) decrease the production of waste; and (3) reduce the environmental impact (Daigle and Lounis, 2006). The availability of literature regarding evaluation of the sustainability of maintenance strategies of corroded RC structures is limited. The work of Daigle and Lounis (2006) presents a comprehensive approach to life-cycle analysis taking into account: (1) costs incurred during construction, maintenance, rehabilitation and replacement; and (2) environmental impact associated with construction and replacement. Such study focuses on patch repair of RC bridges, uses a simplified model of chloride penetration and does not consider the randomness inherent to the phenomenon. Other research efforts have been directed to evaluate environmental impact of concrete with lower content of cementitious material (Kumar Mehta, 2004; Habert and Roussel 2008). These studies search an optimal composition of concrete offering high structural performance and durability. Struble and Godfrey (2004) compared the sustainability of two engineering solutions used to solve the same problem (i.e., RC and steel). They found that RC requires less energy and has a lower net environmental impact than steel.

Maintenance planning of corroding RC structures should combine a comprehensive mathematical model with experimental data. Chloride ingress models should therefore account for the following phenomena: (1) chloride binding capacity of the cementitious system, (2) time-variant nature and effects of temperature, humidity and chloride concentration at the surrounding environment, (3) decrease of chloride diffusivity with concrete age

and (4) flow of chlorides in unsaturated concrete (Saetta et al., 1993; Martín-Pérez et al., 2001). Another key factor influencing the assessment of chloride penetration is the consideration of the uncertainties related to the phenomenon (Bastidas-Arteaga et al. 2009). The sources of uncertainty involved in this problem are related to material properties, model and associated parameters, and environmental actions.

This study focuses on the evaluation of the sustainability of a maintenance strategy for RC structures exposed to chlorides. Maintenance strategies are directed to ensure serviceability and safety during operation life and/or to extend life-cycle of structures. For instance, Figure 1 depicts the impact of two maintenance strategies on the concentration of chlorides at the cover depth –i.e., protective painting and cover rebuilding. These strategies increase the time at which the chloride concentration reaches a threshold C_{th}, reducing the time to corrosion initiation.

The objectives of this paper are:

- to describe the general problem and the criteria for selecting the repair strategy;
- to develop a probabilistic approach to estimate the repair times; and
- to propose a decision-making scheme to compare the sustainability of various repair techniques.

After a general description of the problem (section 2), the selection and description of the repair techniques is presented in section 3. Section 4 discusses the method proposed to assess the schedule of repairs. The sustainability analysis is presented in section 5. Finally a simplified tool for sustainable decision-making is described in section 6.

2. Description of the problem

A major problem in management of RC corroding infrastructure is that there are no decision criteria to compare the performance of the available maintenance solutions. Therefore, owners/operators can incur in additional costs when repairing is undertaken before a given repair threshold is reached, or structural serviceability/safety can be affected when it does not repaired at the appropriated times. This work is carried in the framework of the MAREO[1] project and focuses on the effectiveness, environmental impact and feasibility of maintenance strategies. Towards this aim, this study takes advantage of the know-how of several stakeholders that are connected to the structure during the life-cycle –i.e., owners, designers, contractors, industry sectors, research

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centers, regional interests and government agencies. Thus, a simplified methodology to compare the performance of maintenance strategies in terms of sustainability is developed here. The following paragraphs will present a case study to illustrate the general problem and the criteria taken into consideration to develop the proposed methodology. However, the proposed scheme can be also used to compare other maintenance strategies.

The Agri-foodstuffs terminal of the port of Nantes Saint-Nazaire (Figure 2a) is an example of structures affected by this problem. This terminal is part of the port of Nantes Saint-Nazaire (fourth largest port in France) which is linked to 400 ports worldwide. With a maximal draught of 14 m, the Agri-foodstuffs terminal plans to receive big tonnage ships as container carriers (50,000T). The Port of Nantes Saint-Nazaire is the French market leader for cattle feed imports, with nearly 60% market share. There are four berths at the Agri-foodstuffs terminal, which also handles fertilizers, peat, cement and other miscellaneous industrial bulk products. This wharf was built in 1971 and is located at the west of France (Montoir de Bretagne) in the estuary of the Loire River.

The Autonomous Port of Nantes Saint-Nazaire is the government agency managing the harbor activities of this structure. This agency observed a generalized problem of corrosion affecting mainly the RC beams (Figure 2b) and decided to perform a large-scale repair (Rosquoët et al., 2006). This wharf will be used in this paper to illustrate the formulation of the problem, the requirements of the solution and the proposed methodology.

Figure 3 presents the zone of the Agri-foodstuffs terminal to be repaired. This zone has a triangular form, is 68 m long and 37 m wide. The structure is composed by a RC deck of 0.32 m high, put down on a triangular network of RC beams of 1.00 m side. The beams are supported by steel piles filled with concrete in the upper side. The piles have external diameters of 711, 813 and 914 mm.

3. Description of the maintenance strategy

The maintenance strategy for the Agri-foodstuffs terminal consists basically of rebuilding the polluted concrete cover by various repair techniques. The deteriorated and contaminated concrete is removed using high velocity water jets (hydrodemolition) and the cover is rebuilt by using various techniques. This section presents the techniques used to rebuild the cover of the wharf and that will be compared on the basis of the sustainability. The basic requirements for the selection of the repair techniques are summarized as follows:

- The repair techniques should be easily implemented to repair structural components located in the splash and tidal zones (e.g., beams and piles of wharfs).
- The repair techniques should be applicable to large-scale repairs; local “patch” repairs are beyond the scope of the study.
- The repair materials should have similar composition (i.e., cement-based composition) to focus the analysis on the techniques.

After discussion with the stakeholders participating in the MAREO project, three repair techniques were chosen: (1) *wet shotcrete*; (2) *dry shotcrete* and (3) *formed concrete*. Figure 4 shows a beam after hydrodemolition and the repair techniques to rebuild the cover.

Since there is no previous experience about the performance of the repair materials and techniques, the alternatives selected were tested on twelve chloride-contaminated beams which have been exposed to seawater during 80 years. The beams were part of the structural system of a port built in 1927 at Lorient, France, and demolished in 2006. Figure 5 presents the beams before repair. An important degree of corrosion including cover spalling is observed in all of them. Furthermore, accelerated tests on slabs are being performed in laboratory to characterize the repair materials. Table 1 describes the main characteristics of the repair materials. In general, the materials have a high initial strength, rapid setting, excellent bonding, and a thickness per coat higher than 50 mm.

Based on the data reported by Vilvoisin and Aury (2009) after repair, a comparison among all repair techniques is presented in Table 2. This comparison focuses on: product cost, staff requirements, waste generation and finishing. The staff requirements reported herein correspond to the repair of the testing specimens. Some practical aspects of the repair process showed that the waste production of wet shotcrete is almost negligible, finishing is satisfactory and it can be enhanced by polishing. However, wet shotcrete is the most expensive repair technique, requires the highest number of staff and some cracks were observed after 2-3 days (shrinkage). Although the waste produced by dry shotcrete is the largest, the work area is easily cleaned and the product is ready-to-use, which is convenient for large-scale projects. Given both, its extreme fluidity (no need for vibrators to compact the concrete) and its high workability, the best finished surface corresponds to formed concrete. Yet, the use of such technique is limited to places where the formwork can be placed.

4. Probabilistic assessment of repair times

Given that there is no information about the repair times for each technique, the schedule of repair activities is determined on the basis of a stochastic model of chloride penetration. The proposed methodology implements a comprehensive model of chloride ingress and takes the uncertainty related to the phenomenon into account. This approach is convenient to perform a realistic estimation of the repair times. Section 4.1 outlines the principles of the model of chloride ingress. The section 4.2 presents the probabilistic approach to determine the probability of corrosion initiation which is used in section 4.3 to establish the repair schedule.

4.1. Chloride penetration into concrete

Chloride ingress is controlled by complex interactions between physical and chemical processes, which have been usually simplified as a diffusion problem governed by Fick's second law. Most studies use a simplified solution of Fick's law where the chloride concentration at a given time and position is estimated by an error function complement (Tuutti, 1982). The classical diffusion approach evaluates the apparent diffusion coefficient as constant in time and space, and assumes that the chloride concentration in the surrounding environment remains constant and that concrete is saturated. However, under these simplifications, it is not possible to consider other phenomena as: chloride binding, environmental action, chloride ingress by convection, etc. Based on the work of Saetta et al. (1993) and Martín-Pérez et al. (2001), Bastidas-Arteaga et al. (2009) presented a comprehensive model of chloride penetration. The proposed formulation takes into account the interaction between three phenomena: (1) chloride ingress, (2) moisture diffusion and (3) heat transfer. The coupled phenomena are represented by a set of partial differential equations (PDE) which is solved by coupling finite element and finite difference methods. Such approach accounts mainly for:

- the chloride binding capacity (i.e. interaction between chloride ions and cement paste hydration products);
- the time-variant nature and the influence of temperature, humidity and chloride concentration in the surrounding environment;
- the reduction of chloride diffusivity of RC with age; and
- the chloride flow in unsaturated concrete.

A detailed description of the model is beyond the scope of this paper; it can be found in (Bastidas-Arteaga et al., 2009).

4.2. Probability of corrosion initiation

The time to corrosion initiation, t_{ini}, occurs when the concentration of chlorides at the cover thickness c_t is equal to or higher than a threshold value C_{th}. For such event the limit state function becomes:

$$g(\underline{x},t) = C_{th}(\underline{x}) - C_{tc}(\underline{x},t,c_t) \quad (1)$$

where $\underline{x}$ is the vector of random variables to be taken into account and $C_{tc}(\underline{x}; t; c_t)$ is the total concentration of chlorides at depth c_t and the time t is obtained from the solution of the system of governing equations of chloride ingress. By evaluating the limit state function (Eq. (1)), the probability of corrosion initiation is:

$$p_{corr}(t) = \mathrm{P}\left[g(\underline{x},t) \le 0 \mid t\right] \quad (2)$$

Given the complexity of the solution procedure of the system of PDEs governing the phenomenon, simulation methods seem to be more appropriated to deal with the problem. Therefore, this study combines Monte Carlo simulations with Latin Hypercube sampling to reduce the computational cost. The uncertainties related to the problem are considered by using random variables to represent the model parameters and the material properties, and stochastic processes to model the environmental actions –i.e., temperature, humidity and environmental chloride concentration.

The probabilistic models of the random variables used in this example are shown in Table 3. For chloride ingress, the mean of the reference chloride diffusion coefficient, $D_{c,ref}$, is assigned according to the experimental values presented by Saetta et al. (1993) for a water-cement ratio w/c=0.5. Both the probabilistic model and the COV of $D_{c,ref}$ were defined according to the studies of Val and Trapper (2008) and Duracrete (2000). The statistical parameters of C_{th} are based on the values reported in Vu and Stewart (2000). According to Val and Trapper (2008), the cover thickness, c_t, follows a truncated normal distribution (lower bound) with the mean and COV indicated in Table 3. Based on experimental studies (Page et al., 1981), it is supposed that the activation energy of the chloride diffusion process, U_c, follows a beta distribution. The age reduction factor, m, also follows a beta distribution (Val, 2006). For moisture diffusion, the reference humidity diffusion coefficient, $D_{h,ref}$, is log-normally distributed with mean and COV defined on the basis of (Saetta et al., 1993; Val and Trapper, 2008; Duracrete, 2000). It is also supposed that the parameters α_0 (parameter representing the ratio of $D_{h,min}/D_{h,max}$) and n (parameter characterizing the spread of the drop in D_h) follow a beta distribution with statistical parameters defined according to experimental studies (Bažant and Najjar, 1971 and 1972). For heat transfer, the thermal conductivity of concrete λ and the concrete specific heat capacity c_q, follow beta

distributions with the means reported by Neville (1981) and vary between bounds established experimentally. Taking as mean the typical density of normal concrete, ρ_c, it is assumed that this variable is normally distributed with a COV of 0.2.

After the first repair, the reference chloride diffusion coefficient, $D_{c,ref}$, depends on the properties of the repair material. Since the suppliers do not provided information about this parameter, three reference chloride diffusion coefficients are defined for each technique on the basis of expert judgment:

- Product 1/wet shotcrete: $D_{c,ref} = 3.0 \cdot 10^{-11}$ m^2/s
- Product 2/dry shotcrete: $D_{c,ref} = 4.1 \cdot 10^{-11}$ m^2/s
- Product 3/formed concrete: $D_{c,ref} = 5.2 \cdot 10^{-11}$ m^2/s

These values are adopted as mean for the assessment of the repair times. Based on the values suggested in (Val and Trapper, 2008; Duracrete, 2000), a COV of 0.2 is assumed for all the repair materials.

The influence of weather on chloride ingress is considered by assuming that the structure is placed in an oceanic climate where the mean temperature varies between 5 and 25 ºC, and the mean relative humidity ranges from 0.6 to 0.8. The stochastic nature of weather and environmental chloride concentration is integrated by using the methodology proposed by Bastidas-Arteaga et al. (2009). Figure 6 presents some realizations of temperature and environmental chloride concentrations. To model temperature, a stochastic perturbation is added to a sinusoidal mean trend by using Karhunen-Loève expansion (Ghanem and Spanos, 1991). The truncated expansion series in this model includes 30 terms, the autocorrelation is exponential and the correlation length is 0.1 years. Since several studies indicate that the environmental chloride concentration C_{env} follows a log-normal distribution (Vu and Stewart, 2000; Duracrete, 2000), this work models this variable as a stochastic process generated by independent log-normal numbers (log-normal noise). The mean of C_{env} used to generate the stochastic process is equal to 6 kg/m^3 and corresponds with the boundary value between the high and severe levels of corrosive environment (Weyers, 1994). A coefficient of variation of 0.2 was assumed to model C_{env}.

4.3. Schedule of repair actions

The owners/operators define the schedule of repair actions on the basis of a given criterion related to an allowable damage threshold. The selection of the repair criterion is an important topic in maintenance because it should consider several aspects that differ for particular problems –i.e., economical, environmental, practical, etc. By accounting for the sources of uncertainty described in section 4.2, this work establishes a repair criterion in terms of the probability of corrosion initiation –i.e., Eq. 2 (preventive maintenance). Consequently, the repair

time is defined as the time at which the probability of corrosion initiation reaches a threshold value. The threshold value for the probability of corrosion initiation adopted in this study is 0.95 –i.e., $p_{corr}(t)$=0.95. The owner/operator determines this threshold value in function of its allowable level of corrosion.

This criterion can be considered as conservative in comparison to other criteria found in the literature where repair is carried out after initial or several concrete cracking occurs (e.g., Mullard and Stewart, 2009). However, the criterion proposed herein has been defined after discussion with the stakeholders participating in the MAREO project. The reasons to define this criterion are summarized as follows:

- When the repair criterion is based on the structural condition after corrosion initiation (e.g., concrete cracking), structural safety is affected by the loss of reinforcing steel. Therefore, the assessment of the next repair time should consider the initial structural condition as well as the replacement of the corroded reinforcing steel at a given time. These considerations make the repair scheme complex because (1) repair times are time-dependent and (2) replacement or reinforcement actions should be included in the analysis. Since for the selected criterion repair is carried out before corrosion initiation, it is possible to assume that the repair action is perfect. This means that after each repair the RC member is “as good as new”. Under this assumption, the repair intervals are constant.
- From a practical point of view, the contractors manifest that the replacement of reinforcing bars in existing structures is complicated. Therefore, another advantage of the proposed criterion is that, since repair takes place before corrosion initiation, the replacement of corroded bars is few. However, the condition of reinforcement should be checked before cover rebuilding.
- Finally, this criterion is convenient to combine the maintenance strategy with inspections because it is based on a measurable variable (chloride concentration at the reinforcement depth). Consequently, the owner/operator can evaluate the condition of the structure before repair to calibrate the maintenance schedule.

The assessment of the probability of corrosion initiation for the problem studied in this takes the following assumptions into account:

- the Langmuir isotherm is used to consider chloride binding which coefficients for this case are α_L=0.1185 and β_L=0.09;
- the repair times are established by assuming chloride penetration in one dimension; and
- the random variables are independent and do not vary in the space.

It is important to highlight that the assumptions mentioned previously are used in this work only for illustrative purposes. The hypothesis of chloride diffusion in one dimension should be carefully validated for particular cases. According to Val and Trapper (2008) and Bastidas-Arteaga et al., (2009), chloride penetration in two dimensions should be considered to estimate the probability of corrosion initiation for small structural members as columns and beams. On the other hand, the influence of spatial variability should be also included to improve the assessment of p_{corr}. Stewart (2004) presents a comprehensive approach to account for the spatial variability of corroding RC beams in flexure and studies its influence on reliability. An application of this methodology to the stochastic assessment of repair times and the evaluation of efficiency of maintenance is presented in (Mullard and Stewart, 2009).

The probability of corrosion initiation for the selected repair materials is presented in Figure 7. As expected, p_{corr} increases for the materials with larger chloride diffusivity. Then, the length of the repair time, t_r, for each material/technique are:

- Product 1/wet shotcrete: t_r=30 yr,
- Product 2/dry shotcrete: t_r=20 yr, and
- Product 3/formed concrete: t_r=15 yr.

It can be noted that the larger repair time correspond to the material with lower chloride diffusivity. It is paramount to clarify that the reported repair times are illustrative. Since the coefficients of diffusion were defined on the basis of expert judgment, these repair times show the tendency of the overall behavior. Therefore, these coefficients should be determined experimentally to improve the accuracy of the assessment. Taking into consideration these repair times, Table 4 presents the schedule of the repairs for each repair technique. Given that the construction material is the same before repair actions are performed, it is found that the first repair should be carried out after 15 years of exposure for all alternatives. Three life-cycle lengths are also included in the analysis –i.e., T = 50, T = 75 and T = 100 years. The overall behavior indicates that the minor number of repairs corresponds to the alternative with larger repair time (wet shotcrete), followed by dry shotcrete and formed concrete.

5. Criteria to evaluate the sustainability

The world commission on environment and development (1987) defines sustainable development as: '*development that meets the needs of the present without compromising the ability of future generations to meet*

their own needs'. According to Struble and Godfrey (2004), there are three components of sustainability: environment, economy and society. To meet its goal, sustainable development must provide a balance between these components (Sánchez-Silva and Rosowsky, 2008). The sustainability analysis carried out in this work accounts principally for the environmental and economical components. However, society is directly implied to decisions affecting these components. Thus, the evaluation of the sustainability of the repair techniques is based on the comparison of three criteria:

1. present value life-cycle cost,
2. waste production, and
3. CO_2 emissions.

This section discusses the performance of the repair techniques for each criterion separately. Based on this comparison, section 6 proposes a simplified scheme for decision-making.

5.1. Life-cycle cost analysis

The comparison between the costs for the selected repair techniques is carried out in terms of life-cycle cost analysis (LCCA). LCCA is used to estimate the total cost when the costs of inspection, repair and rehabilitation activities incurred at different times. The present value life-cycle cost (PVLCC) of a structure over a given life-cycle T, assuming a constant discount rate r, is given by (Daigle and Lounis, 2006):

$$PVLCC = C_0 + \sum_{t_i=1}^{T} \frac{C_i(t_i)}{(1+r)^{t_i}} - \frac{R_v}{(1+r)^T} \tag{3}$$

where C_0 is the initial construction cost (including design costs), $C_i(t_i)$ is the i^{th} expenditure at time t_i (e.g., inspection, maintenance, repair, demolition, disposal, etc.) and R_v is the residual (or salvage) value at the end of the life-cycle.

Two kinds of costs are usually considered in life-cycle cost analysis: 'agency' and 'user' costs. Agency costs encompass the direct costs incurred by the owner/operator during the life-cycle including initial construction costs and costs associated with inspection, repair, rehabilitation, replacement and disposal. User costs represent the inconvenience and expenses incurred by the users due to traffic disruption as travel delay costs, ship operating costs and accident costs. According to Thoft-Christensen (2009), user costs should be included in the analysis to formulate a comprehensive strategy of maintenance management of bridges. However, given that the information to estimate user costs for harbor structures is unavailable; this work is only based on agency costs.

Since this study focuses on repair of RC structures, the direct costs incurred by the agency include only costs associated with repair. The initial construction costs are not included in the analysis because it is assumed that it would be the same for all alternatives. Since it is not possible to determine the final use of the structure at the end of the life-cycle (deconstruction or demolition), the residual (or salvage) value is not considered. Thus, Table 5 presents the agency costs estimated for a single repair operation. To give an idea of the cost per quantity of repaired concrete (in €/m3), the total repair cost is divided by the volume of concrete repaired. Such costs were estimated based on the repair experience reported in section 3 (e.g., Table 2) and include costs related to hydrodemolition of the polluted concrete, cover rebuilding, labor, equipments (rental), form, transport and waste disposal.

Based on the repair schedule computed in section 4.4 and the agency costs presented in Table 5, the present value of life-cycle agency costs for all the techniques and the life-cycle lengths are presented in Figure 8. The PVLCC analysis indicates that the formed concrete is the cheapest alternative for all life-cycle lengths. It is observed that the life-cycle length can influence the choice of a given technique. For instance, although the PVLCC analysis for T=50 yr indicates that wet concrete is the more expensive alternative, for T=75 and T=100 yr this might not be the case. Such behavior indicates that life-cycle length is a key parameter which should be carefully chosen by the agency.

5.2. Waste generation

Waste generation is basically computed by estimating the volume of repaired material and the waste generated during the rebuilding process. Figure 9a shows the comparison of the waste produced for a single repair operation. The waste generation is expressed in percentage of waste generation compared to repaired material; then the waste produced by hydrodemolition is equal to 100%. For cover rebuilding, waste production is estimated by taking the values measured during the repairs into account –i.e., Table 2. Although the highest production of waste corresponds to the demolition, there is a large loss of material for the dry shotcrete technique.

Figure 9b presents the waste generated for each alternative during the considered life-cycles. As expected, the production of waste materials is higher for the alternatives with an important number of interventions and/or larger loss of material during the repair process (dry shotcrete and formed concrete). Thus, given both its lower number of interventions and its smaller lost of materials, it is concluded that, from the point of view of waste generation, wet shotcrete has a positive effect on the environment.

5.3. Carbon dioxide emissions

For this analysis two sources of carbon dioxide are considered:

1. emissions produced during transportation of materials, equipments and waste, and
2. CO_2 released during production of the repair material.

According to Norton et al., (1998) it is assumed in this paper that the average emission of CO_2 for a truck is 1700 grams of CO_2 per km. This estimation also supposes that all transportation of materials and waste is carried out in a standard truck with a capacity of 8 m^3. The distances of provisioning of materials and equipments and disposal of waste are 100 and 150 km, respectively. According to the International Energy Agency (2007), the average CO_2 emissions range from 0.65 to 0.92 ton of CO_2 per ton of cement across several countries. Since there is no information about the CO_2 emissions related to the production of the repair products, a weighted average emission of 0.83 ton CO_2 /ton is adopted herein for all the repair products.

Figure 10a depicts the emissions of CO_2 per volume of concrete repaired (in kg CO_2/m^3) for source and repair strategy. These results were obtained for a single repair operation. For all the techniques, it is observed that the emissions released during the production correspond to about 75% of the total. Therefore current research efforts should be addressed to reduce the production emissions. For a single repair operation, the emissions released during wet shotcrete and formed concrete are almost the same, whereas dry shotcrete is more contaminant. This behavior is explained by the fact that for the same volume of repaired concrete, dry shotcrete requires a higher quantity of material (30% of waste generation –i.e., Table 2) increasing the emissions of transportation and production.

The comparison of the emissions of CO_2 for all the repair techniques during the life-cycle is presented in Figure 10b. Wet shotcrete is the cleaner alternative for all the lengths of the life-cycle because the reduced number of repairs diminishes the emissions of CO_2. For a life-cycle length of 100 years this difference is about the half of the emissions produced by formed concrete. Therefore, by comparing in terms of waste generation and CO_2 emissions, it can be concluded that wet shotcrete is the cleaner alternative for projects with larger life-cycle length.

6. Sustainable decision-making

This section presents a simplified decision-making scheme which is based on multi-criteria comparison of the selected repair techniques. This scheme has been formulated based on the stakeholders' feedback and aims to

develop a simplified tool to compare the performance of the repair techniques from an economical and environmental point of view. This comparative analysis includes the three criteria described in section 5: (1) present value life-cycle cost, (2) waste production, and (3) CO_2 emissions. Since these criteria are quantified in their own type of units, the results are classified, based on its performance, as 1, 2 or 3. Therefore, 1 is given to the alternative with the worst performance and 3 to the repair technique with best performance per criteria. For instance, 1 indicates that such alternative is more expensive and pollutant in terms of both waste generation and CO_2 emissions.

On the basis of this new classification, Figure 11 presents the multi-criteria comparison for the studied repair techniques. These results indicate that there are two optimal solutions in this case: wet shotcrete and formed concrete. For life-cycle lengths higher than 50 years, wet shotcrete is the more environmentally friendly alternative although expensive. Formed concrete is the cheapest alternative; however, its environmental performance is very low. Dry shotcrete could be implemented for life-cycles lower than 50 years. Nevertheless, for $T > 50$ years, this option becomes unattractive due to both the high environmental impact and the costs. The choice of a given strategy depends on many factors as life-cycle length, availability of resources and other agency's policies.

Figure 11 presents a useful scheme oriented to increase owners' awareness concerning to environmental problems. However, it illustrates the conflicting nature of these criteria and the difficulty in prioritizing. For this problem, an optimal solution should minimize the costs and the environmental impact. The optimal solution can be found by using multi-objective optimization. There are several approaches to solve multi-objective optimization problems: multi-attribute utility theory, weighted sum approach, compromise programming, constraint approach, and sequential optimization (Lounis, 2006). This paper adopts compromise programming to solve the multi-objective maintenance optimization problem. The solution of this optimization technique minimizes the distance from the set of Pareto optima to the so-called 'ideal solution'. The ideal solution is defined as the solution that yields simultaneously optimum values for all objectives. For *m* objective functions, the ideal solution can be associated with the following ideal objective vector:

$$\mathbf{f}^* = \left[\min f_1(x) \quad \min f_2(x) \quad \cdots \quad \min f_m(x)\right] \tag{4}$$

Since each criterion has an own system of units, this paper uses a multi-objective index (MOI) to determine the optimal technique (Lounis, 2006). MOI is defined as the value of the weighted and normalized

deviation from the ideal solution $\mathbf{f}^*$ measured by the family of L_p metrics. Thus, the 'satisfying' solution is the one that yields a minimum MOI:

$$MOI_p(x) = \left[\sum_{i=i}^{m} w_i^p \left| \frac{f_i(x) - \min f_i(x)}{\max f_i(x) - \min f_i(x)} \right|^p \right]^{1/p} \quad (5)$$

where w_i are the weighting factors of the optimization criteria f_i (i =1,...,m) and p is a parameter indicating the importance given to different deviations from the ideal solution. The value of w_i depends mainly on the attitude of the owner/operator towards each criterion. The parameter p varies between 1 and ∞. For p = 1, all deviations from the ideal solution are considered in direct proportion to their magnitudes, which corresponds to a group utility (Duckstein 1984). For p = 2, a greater weight is associated with the larger deviations from the ideal solution and L_2 represents the Euclidian metric. For p =∞, the largest deviation is the only one taken into account and is referred to as the Chebyshev metric or mini-max criterion and L_∞ corresponds to a purely individual utility (Lounis 2006). This paper considers the Euclidean metrics to determine the MOI, and consequently, the corresponding satisfying technique.

Table 6 summarizes the PVLCC, waste generation and CO_2 emissions for each technique for T = 50 yr. It is observed that there is no an 'ideal' alternative that minimizes the tree criteria. Then, the ideal objective vector is $\mathbf{f}^*$=[2910€/m^3, 210% and 1171 kg CO_2/m^3]. Figure 12 presents a multi-criteria prioritization of the repair techniques based on the Euclidean MOI –i.e., Eq. 5. This analysis considers that all criteria have the same weighting factors (w_i = 1). This means that the owner/operator have no priorities for choosing an alternative. However, these factors can be modified when the project is regulated by environmental or economical constrains. The comparison of the Euclidean MOI indicates that the selection of an optimal alternative depends on the length of the life-cycle. The optimal solution is dry shotcrete for T= 50 years, whereas is wet shotcrete for T > 50 years. Although formed concrete is the cheapest solution, this alternative is far to be optimal because has been penalized by its high environmental impact.

Conclusions and further work

This paper presented an approach for evaluating the sustainability of repair strategies for chloride-contaminated RC structures. The proposed methodology was illustrated throughout the paper evaluating the sustainability of large-scale maintenance of a real structure. The repair techniques (wet shotcrete, dry shotcrete and formed

concrete) were tested on beams exposed to chlorides during 80 years to introduce real input data in our models. The repair times for each technique were computed based on a probabilistic assessment that accounted for the randomness of material properties, model and weather. The evaluation of sustainability was based on the comparison of three criteria (1) present value life-cycle cost, (2) waste production and (3) CO_2 emissions. A simplified decision-making scheme is proposed based on a multi-objective index. This decision-making tool can be used by the owners to search a solution optimizing costs and reducing environmental impact. Based on these results, further work in this area is addressed to:

- characterize of repair products: diffusion coefficient, binding isotherm parameters, etc. This study is being performed by normal and accelerated tests;
- account for spatial variability of the random variables;
- integrate user costs to the analysis;
- include the uncertainty inherent to waste generation and CO_2 emissions; and
- optimize the efficiency of the repair techniques in terms of costs and environmental impact.

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Table 1. Main features of the selected repair materials.

Features	Product 1 / wet shotcrete	Product 2 / dry shotcrete	Product 3 / formed concrete
Initial strength	20 MPa in 24 hours	11 MPa in 3 hours	4 MPa in 3 hours
Thickness per coat	to up 50 mm	to up 100 mm	to up 100 mm
setting	Rapid	Rapid	Rapid
bonding	Excellent	Excellent	Excellent

Table 2. Comparison between products and repair techniques.

Criteria	Product 1 / wet shotcrete	Product 2 / dry shotcrete	Product 3 / formed concrete
product cost	17€ / 25 kg	7€ / 25 kg	5€ / 35 kg
staff	5 people	3 people	2 people
waste generation	not significant <5%	important > 30%	not significant <5%
finished	satisfactory	rough	very satisfactory

Table 3. Probabilistic parameters of the variables.

Physical problem	Var.	Units	Distribution	Mean	COV
Chloride ingress	$D_{c,ref}$	m^2/s	log-normal	$3 \cdot 10^{-11}$	0.20
	C_{th}	kg/m^3	normal	0.70	0.30
	c_t	mm	normal (trunc. at 10mm)	50	0.25
	U_c	kJ/mol	beta on [32;44.6]	41.8	0.10
	m		beta on [0;1]	0.15	0.30
Moisture diffusion	$D_{h,ref}$	m^2/s	log-normal	$3 \cdot 10^{-10}$	0.20
	α_0		beta on [0.025;0.1]	0.05	0.20
	n		beta on [6;16]	11	0.10
Heat transfer	λ	W/(m°C)	beta on [1.4;3.6]	2.5	0.20
	c_q	J/(kg°C)	beta on [840;1170]	1000	0.10
	ρ_c	kg/m^3	normal	2400	0.20

Table 4. Schedule of repair activities.

Life-cycle length (yrs)	Wet shotcrete		Dry shotcrete		Formed concrete	
	No. of Repairs	Specific schedule (yrs)	No. of Repairs	Specific schedule (yrs)	No. of Repairs	Specific schedule (yrs)
T = 50	2	15, 45	2	15, 35	3	15, 30, 45
T = 75	2	15, 45	3	15, 35, 55	4	15, 30, 45, 60
T = 100	3	15, 45, 75	5	15, 35, 55, 75, 95	6	15, 30, 45, 60, 75, 90

Table 5. Computed agency costs.

Item	Wet shotcrete €/m^3	Dry shotcrete €/m^3	Formed concrete €/m^3
Hydrodemolition	1500	1500	1500
Recovery, treatment and disposal of waste	172	172	172
Materials	1309	828	250
Labor	685	418	192
Equipments	183	210	94
Total	*3848*	*3128*	*2208*

Table 6. PVLCC, waste generation and CO_2 emissions for each technique for T=50 years.

Repair technique	Optimization criteria		
	PVLCC €/m^3	Waste generation %	CO_2 emissions kg CO_2/m^3
Wet shotcrete	3487	*210*	*1171*
Dry shotcrete	3119	260	1431
Formed concrete	*2910*	315	1804

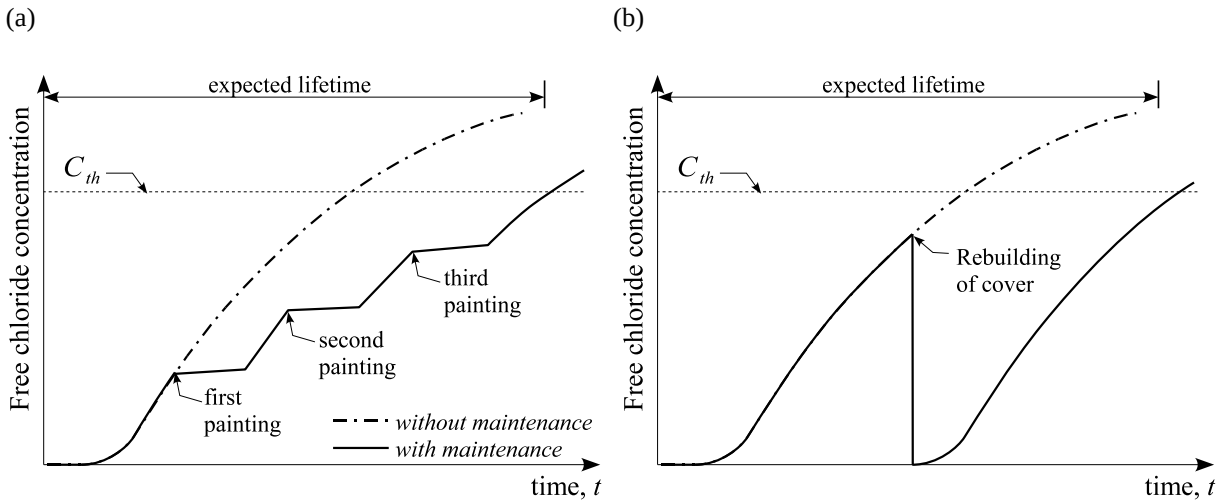


Figure 1. Maintenance strategies: (a) protective painting, (b) cover rebuilding

(a) (b)

Figure 2. (a) Agri-foodstuffs terminal. (b) Corroded beams.

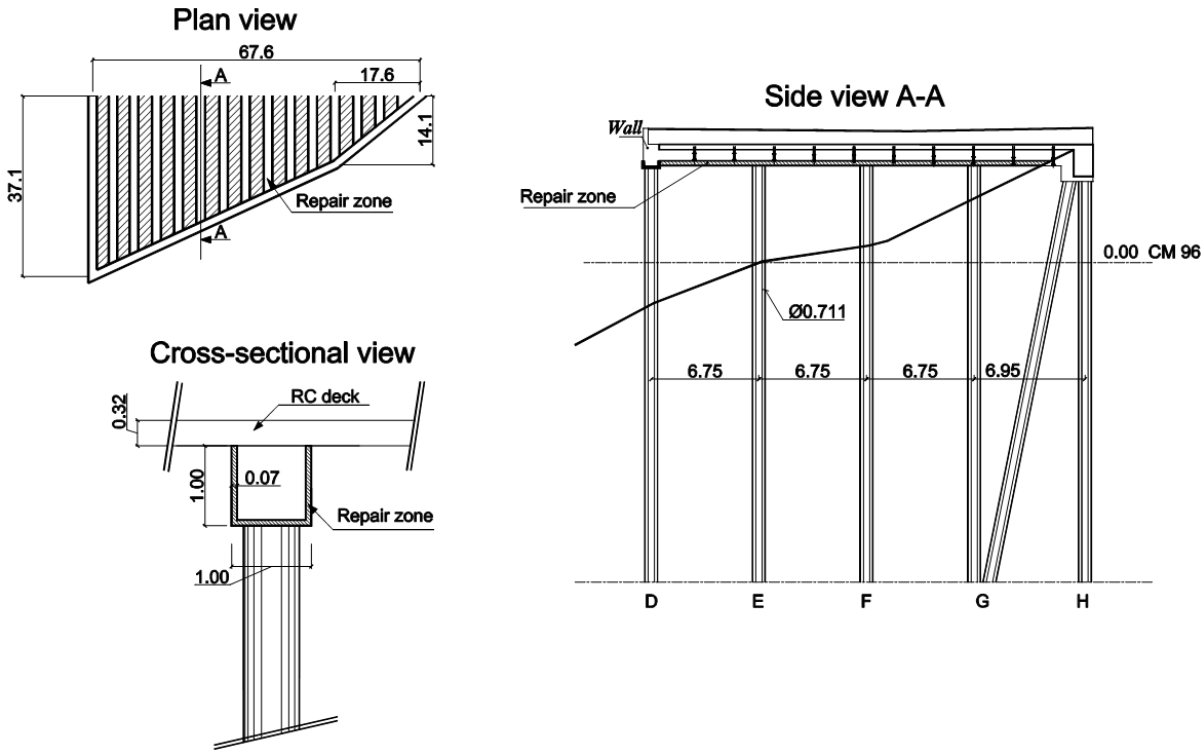


Figure 3. Zone of the Agri-foodstuffs terminal to be repaired.

(a) (b) (c)

Figure 4. Repair techniques: (a) beam after hydrodemolition, (b) wet/dry shotcrete(c) formed concrete.

Figure 5. Beams after 80 years of exposure.

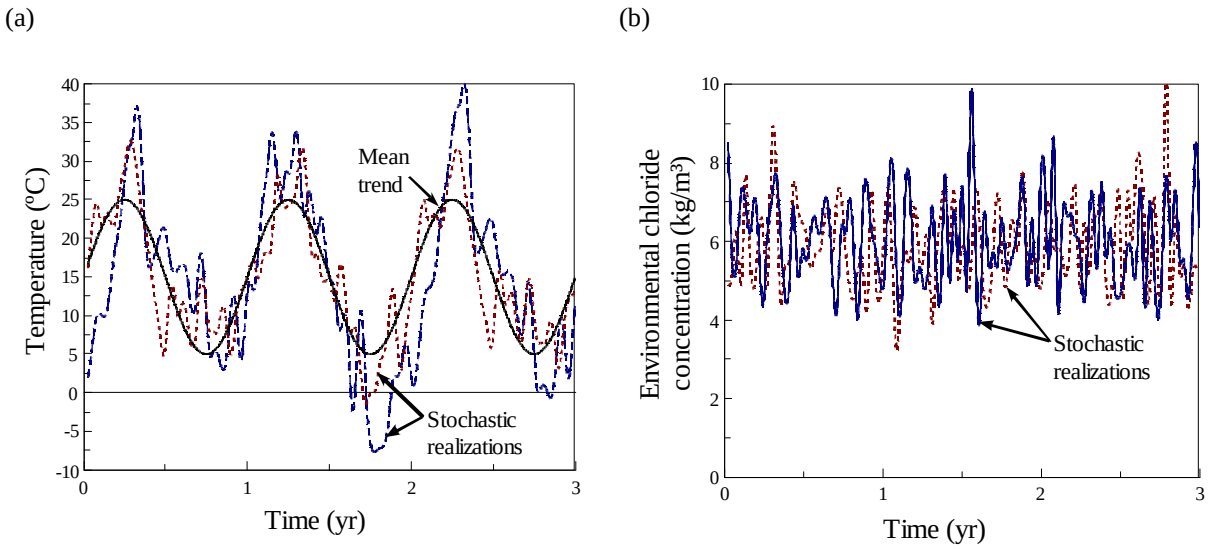


Figure 6. Stochastic inputs of: (a) weather, (b) environmental chloride concentration.

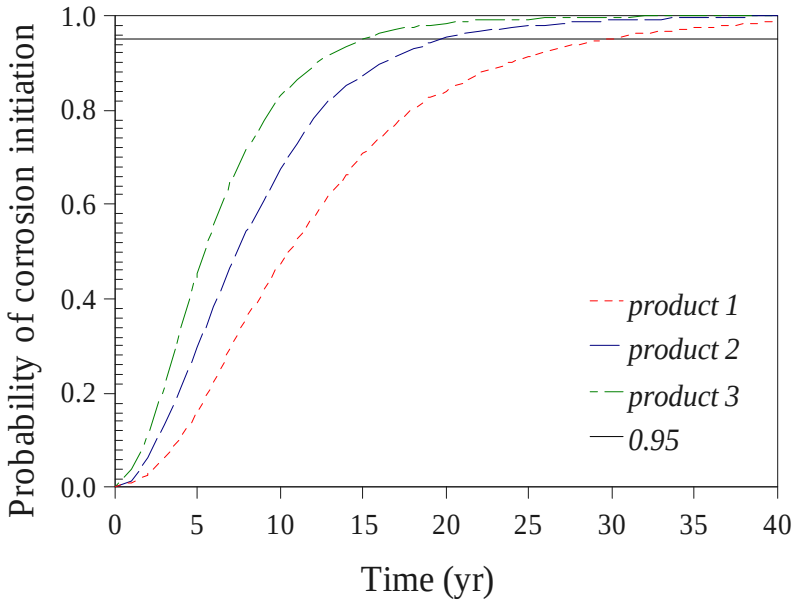


Figure 7. Probability of corrosion initiation for the repair materials.

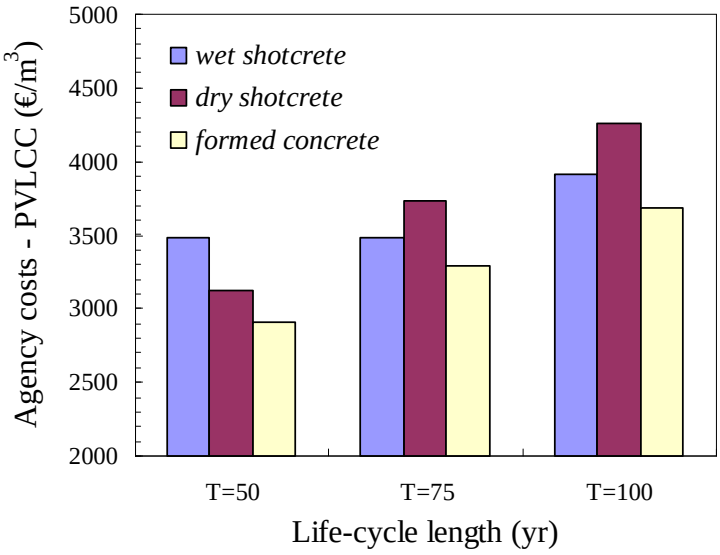


Figure 8. Present value of life-cycle agency cost.

(a) (b)

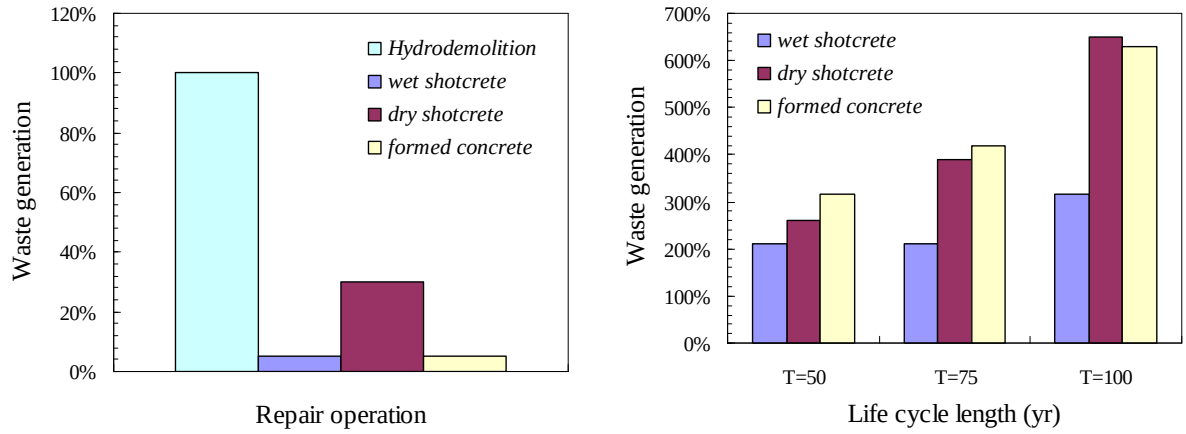


Figure 9. Waste generation for (a) repair operation and (b) repair techniques during the life-cycle.

(a) (b)

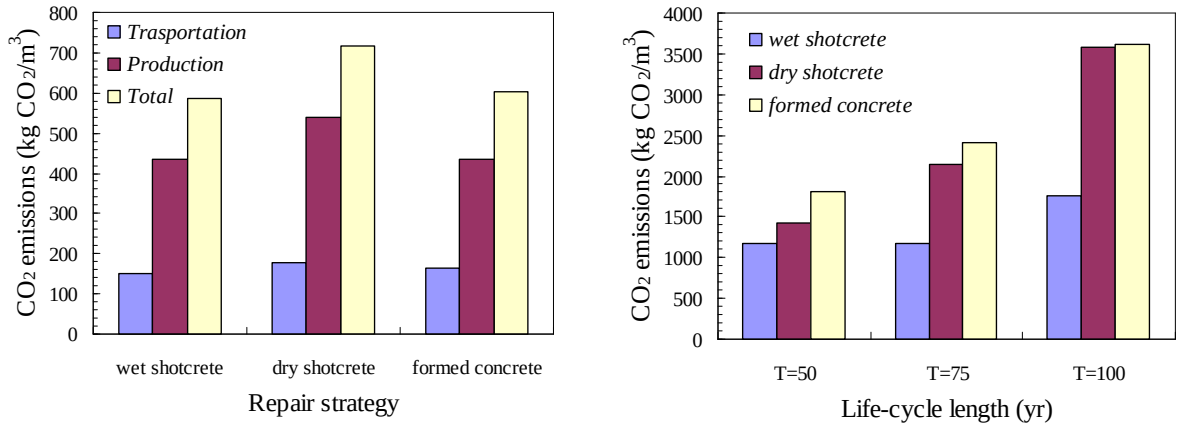
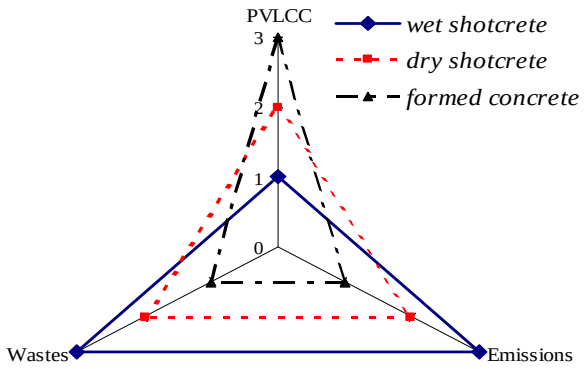
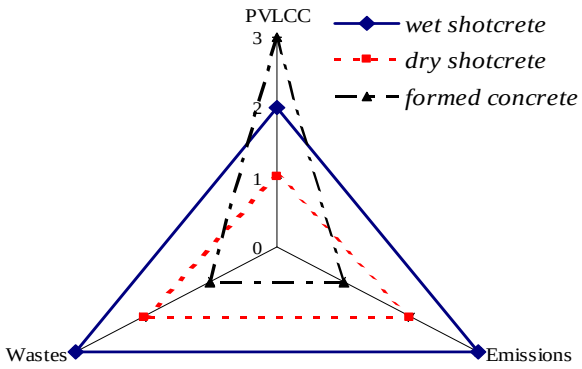


Figure 10. Emissions of CO_2 for: (a) source, and (b) during the life-cycle.

(a)



(b)



(c)

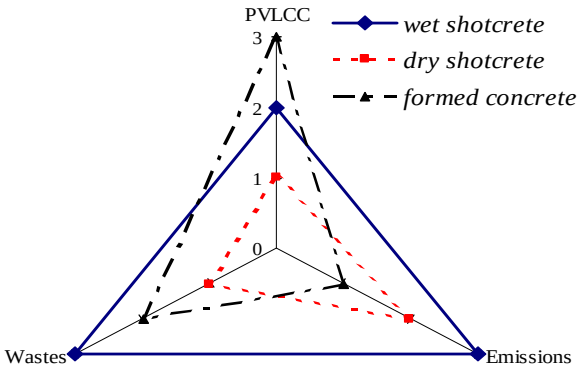


Figure 11. Multi-criteria comparison. (a) T=50 yr, (b) T=75 yr and (c) T= 100 yr.

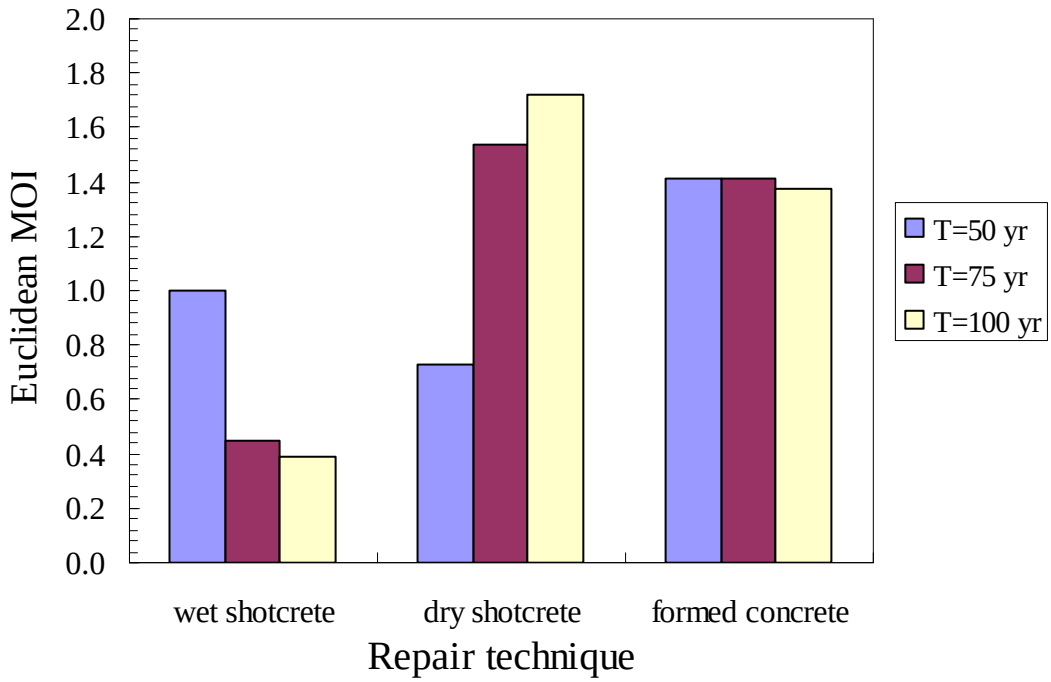


Figure 12. Multi-criteria prioritization of the repair techniques.