Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

LCA assessment related to the evolution of the earthquake performance of a strategic structure

D. di Summa
Ghent University, Ghent, Belgium
Politecnico di Milano, Milan, Italy

A. Marcucci, M. Nicolò, F. Martignoni, A. Carrassi & L. Ferrara
Politecnico di Milano, Milan, Italy

N. De Belie
Ghent University, Ghent, Belgium

ABSTRACT: Several buildings and infrastructures, located in urban areas, are identified as strategic in the case of an earthquake event. This is the case of a water treatment plant which is currently built in Genoa, Italy, and which has been assessed for the scope of this research. Since the structure has been designed following the seismic design prescriptions, this work aims to provide a preliminary assessment of how the degradation mechanisms do affect its earthquake response. To this purpose, both chloride attack and carbonation are taken into account as main degradation mechanisms. Moreover, due to the importance of the water treatment plant, to develop a realistic Life Cycle Assessment (LCA) analysis, the earthquake resistance of the structure and its evolution over time as a function of the aforesaid degradation mechanisms, have been accounted as Serviceability Limit State to estimate the frequency of the maintenance activities needed in a timeframe of 100 years.

1 INTRODUCTION

Nowadays, the large use of concrete within the construction sector outlines the need to investigate in deep the degradation phenomena that occur over the time in which a structure, an infrastructure or, simply, a structural element is designed to ensure an adequate serviceability. This, also in view of the environmental, economic and social consequences associated to the production of cement-based materials in general when not characterized by an appropriate durability. As an example, not only the production of all concrete components, including Portland Cement (PC) that is responsible for 2 billion tons/year of CO_2 (Szabo et al., 2006) (Turner & Collins, 2013)(Ouellet-Plamondon & Habert, 2015)(McLellan et al., 2011), must be taken into consideration, but also the maintenance activities that could contribute to 55% of the CO_2 emissions generated from the construction phase until the dismission of a structure (Kumanayake & Luo, 2018). These data, when referred to the worldwide total production of concrete per year, clearly highlight the magnitude of the overall sustainability issue that, as stated by Huntzingar and Eatmon (2008) can be at local, global or regional scale. To overcome the latter, some studies focused their attention, in the recent past, on the development of advanced cement based materials such as the self-healing ones, able to restore their integrity in the case of a crack creation (Shields et al., 2021)(di Summa et al., 2022)(Van den heede et al., 2018)(Cappellesso et al., 2023). Moreover, the behaviour of concrete when exposed to aggressive environmental scenarios (e.g. carbonation or chlorides penetration) generated an increasing interest also because of the market awareness regarding the need of having long durability, reduced maintenance costs and adequate environmental performance. In this framework, the scope of this investigation is to address the effects that certain aggressive

DOI: 10.1201/9781003323020-143

degradation phenomena have on the structural performance of a construction in the event of an earthquake. More specifically, the largest water treatment plant within Northern Europe, identified as a strategic structure, has been assessed. Moreover, the moment when a specific damage affects the structural performance is taken into consideration as serviceability limit state in correspondence of which the maintenance activities have to be carried out to restore the normal functionality. Thus, the Life Cycle Assessment (LCA) methodology has been employed to assess the environmental performance within the defined service life (SL). In line with other researches (Kannikachalam et al., 2022)(di Summa et al., 2022)(Al-Obaidi et al., 2021)(Al-Obaidi et al.2022), the idea is to propose an approach that can help the decision process of the designers, accounting for, a priori, the overall sustainability performance due to the interaction of the material with the surrounding environment. Such approach could be then replicated, in the future, for strategic structures similar to the one here assessed.

2 DESCRIPTION OF THE CASE STUDY AND DEGRADATION MECHANISMS

2.1 *Description of the case study*

The water treatment structure is located in Genoa, northern Italy, within the port area and aimed at serving a population of 250,000 inhabitants. It has been identified as a strategic structure in the case of an earthquake event, reason why a SL equal to 100 years has been taken into consideration for the following analysis. A frame structure, with beams which are sometimes eccentric in relation to the corresponding pillars, characterizes the ground level. The beams have a cross section equal to 0.70m x 0.70m or 0.70m x 1.00m, the pillars of 0.70m x 0.70m while the walls of the basins at the first floor have a thickness varying between 0.30m and 0.25m. Figure 1 gives an overview of the layout of the entire structure. To have a complete knowledge of the structure, the behaviour in the event of an earthquake has been assessed prior to estimating the durability of the construction within the SL. This was possible by carrying out a modal analysis in which the vibration response has been identified for each element of the structure. Figure 1 also details a vibration example in which it is possible to highlight how the overall behaviour is not uniform. The analysis hereinafter presented is focused on the 26 pillars of the structure. The pillars are characterized by 24 Φ24 steel reinforcement bars equally located along the 4 sides. They are subjected to a biaxial compression and bending with an average axial force of 2,300 kN and the highest value of the acting bending moment (M_{Ed}) is equal to 1200 kNm. Figure 2 details the cross section of the pillars besides the M-N interaction diagrams due to the eccentric axial force. The structure being located at the seaside and being characterized by an XS1 exposure class, both the carbonation and the chlorides penetration phenomena have been taken into consideration. With regard to the concrete, the structure has been realized by employing ordinary reinforced concrete (ORC) and ORC containing crystalline admixture (1% by mass of cement). The latter was added to enhance not only the self-healing properties but also to reduce the permeability of the concrete, avoiding the ingress of harmful substances. Even though the pillars have been realized without the addition of the crystalline admixture (CA), hereinafter two cases are assessed. The first one, corresponding to the reality, with the pillars made with ORC (referred as P_ORC) and the second one, purely hypothetical, in which they are made with the addition of the crystalline admixture (referred as P_CA).

2.2 *Carbonation*

To estimate the carbonation penetration, 12 cube specimens (150mm x 150mm) have been cast during the structure casting phases (March 2022). Half of the specimens were realized with the mix design of P_ORC while the remaining ones with the one of P_CA. With regard to the carbonation tests, after being exposed to open air within the worksite for 3, 6 and 9 months, as shown in Figure 3 each specimen was split into two halves and each half was then divided in two equal parts to have two perpendicular areas on which phenolphthalein was then sprayed. Table 1 indicates the average penetration depth achieved after 3 months and 6 months respectively and it is also possible to observe an overall better performance of P_CA at both ages.

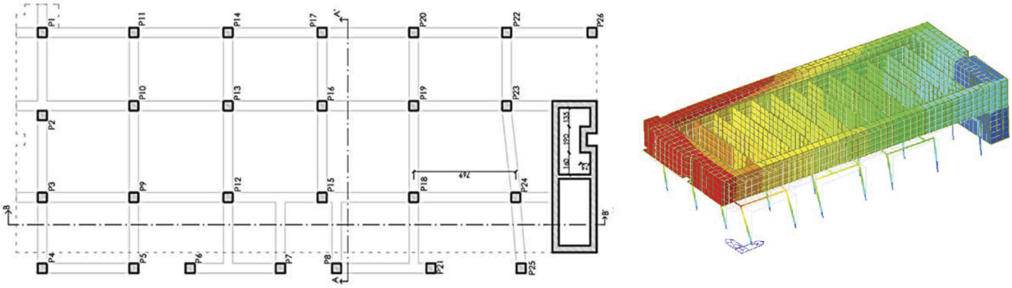

Figure 1. Layout of the structure (left) and the vibration response (right) in which the color red represents the parts more vulnerable to vibration.

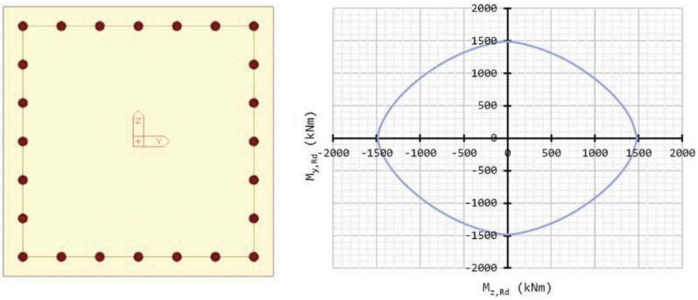

Figure 2. Cross section of the pillars (left) and biaxial interaction diagram due to an eccentric axial force.

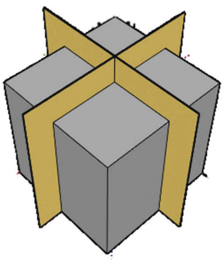

Figure 3. Example of the division of the specimen to spray the phenolphthalein.

Table 1. Carbonation depth (mm), Average and standard deviation after 3, 6 and 9 months.

	Average	SD
P_ORC (3 months)	3.8	0.60
P_ CA (3 months)	1.72	0.35
P_ORC (6 months)	3.92	0.33
P_CA (6 months)	2.54	0.53
P_ORC (9 months)	4.3	0.75
P_CA (9 months)	3.03	0.25

The values presented in Table 1 have been then employed to predict the evolution of the carbonation over the SL of the structure through Equation 1 where x_c represents the depth of the carbonation, t the time expressed in years, W(t) a weather function used to consider the time in which the concrete is wet and k is the carbonation coefficient measured in mm/(years)$^{0.5}$. The latter depends on several factors such as water to cement ratio, relative humidity and CO_2 concentration. While W(t) has been assumed as equal to 1 due to the fact that the pillars are inside a prefabricated structure and, then, they are not wet, *k* has been determined by employing a non-linear regression analysis for Equation 1 and using the values reported in Table 1. The values obtained were 6.23 mm/(years)$^{0.5}$ for P_ORC and 3.53 mm/(years)$^{0.5}$ for P_CA. Thus, it was then possible to calculate the time needed for the carbonation process to reach the reinforcement bar surfaces located at a depth of 0.40mm according to the standards prescriptions for structures exposed to a XS1 environment. This corresponded to 41.3 years for P_ORC and 128.1 years for P_ CA.

$$x_c = W(t)k\sqrt{t} \tag{1}$$

The result of P_CA being even higher than the accounted SL, the reduction of the diameter of the steel reinforcement bars have been estimated only for P_ORC by employing Equation 2 in which ϕ_o represents the initial diameter of the reinforcement (mm), t the time (years), t_{in} is the time that the carbonation needs to reach the steel bars surface. Moreover, *j* is a constant equal to 0.0116 for the case of the steel and i_{corr} represents the power intensity in μA/cm^2 assumed as equal to 0.5 μA/cm^2 for the scope of this analysis according to (Bertolini & Pedeferri, 1996).

$$\phi(t) = \phi_0 - 2i_{corr}j(\mathrm{t} - \mathrm{t_n}) \tag{2}$$

By employing Equation 2 it has been possible to estimate for P_ORC, a reduction of the cross section of each bar equal to 5.60% at the time of 100 years. These results are reported in Figure 3 which also contains the behaviour that the bars would have had in the case of P_CA. Then, following the model proposed by Maaddawy (El Maaddawy & Soudky, 2006) the time needed to form the first cracks because of the expansion products of the corrosion has been calculated. Such phenomenon is dictated by the thickness of the concrete cover, the diameter and the expansion volume of the steel bars, the elastic modulus of concrete and the thickness of the porous layer between concrete and steel. It was then estimated that the complete detachment of the concrete cover happens 11 years after the corrosion onset, in correspondence of the obtainment of 1 mm cracks, meaning after 52 years in total for P_ORC. Nevertheless, it must be specified that these results have to be considered as optimistic predictions since they are referring to a non-cracked state which is practically never achievable in the reality.

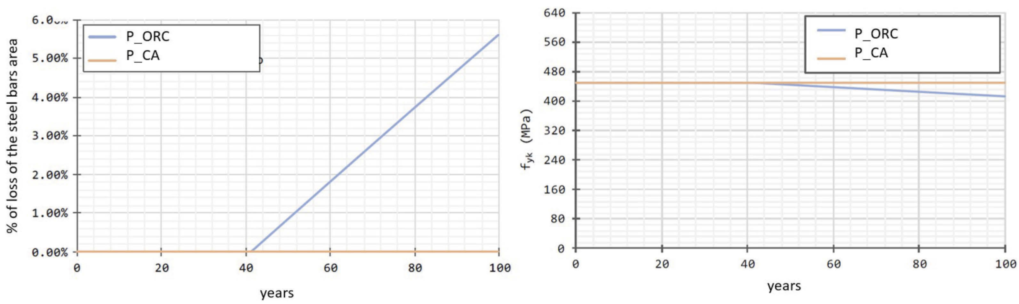

Figure 4. Loss of the cross section of the reinforcement bars in percentage (left) and decrease of steel tensile strength (F_{yk}).

2.3 *Chlorides induced corrosion*

As for the carbonation tests, 12 cubic specimens (150 mm x 150 mm) were realized during the casting procedures and were then split along two perpendicular areas to spray the 0.1-N $AgNO_3$ solution and check the chlorides penetration after 3 and 6 months of exposure to open air. Also in this case the results have shown a better performance for the case of the mix design of P_CA. Table 2 reports the value observed for the chloride penetration.

Table 2. Chlorides depth (mm), Average and standard deviation after 3, 6 and 9 months.

	Average	SD
P_ORC (3 months)	1.24	0.45
P_ CA (3 months)	0.97	0.34
P_ORC (6 months)	2.10	0.81
P_CA (6 months)	1.13	0.22
P_ORC (9 months)	3.03	0.57
P_CA (9 months)	2.10	0.64

The values presented in Table 2 have then been used to calculate the apparent chloride diffusion coefficient (D_{app}) which, as already highlighted in other works (di Summa et al., 2022) (Cappellesso et al., 2023)(Kannikachalam et al., 2023) is a key parameter to predict the penetration of the chlorides within a certain time. Thus, considering a critical chloride content equal to 0.11% by weight of concrete as in (Stipanovic Oslakovic et. al, 2008), it has been possible to calculate a value of 9 x 10^{-13} m^2/s and 3.4 x 10^{-13} m^2/s for P_ORC and P_ CA respectively by employing the second Fick's law. Figure 5 provides an overview of the chloride content for both P_ORC and P_CA at the age of 20, 40, 60, 100, 140 and 180 years for which both Cs and Dapp have been assumed as constant over the time for the scope of these calculations. As it is possible to observe, the latter is reached, in correspondence of the reinforcement bars surface (namely 40 mm as the designed concrete cover) after 137 years for P_ORC and after more than 300 years for the case of P_CA. These years correspond to the corrosion initiation time. Moreover, considering that these values are based on the results obtained from the experimental campaign conducted on the uncracked state the influence of the cracks on the D_{app} value has also been checked. More specifically, considering a crack opening equal to 0.2 mm as suggested for the assumed environmental condition in the Eurocode and employing the model suggested by Wang et al., (Wang et al., 2022) an initiation time equal to 82 years for P_ORC and 135 years for P_CA was then calculated. Both periods are much higher than the ones previously estimated for the carbonation.

2.4 *Structural performances of the case study subjected to the degradation phenomena*

According to what has been stated in sections 2.2 and 2.3, P_ORC has a worse durability performance for both carbonation and chlorides penetration. Therefore, also its structural performance has been checked within the SL. More specifically, since carbonation is the degradation phenomenon which first leads to the reduction of the reinforcement cross section in the columns, it is the one hereinafter taken into account. Thus, the following timeframes have been assessed for the scope of the structural analysis: i) from 0 to 41 years, during when the cross section of the column doesn't show any variation; ii) from 42 to 51 years, when the corrosion starts to occur with the consequent cracks creation; iii) from 52 to 100 years, when, if no maintenance activities are going to be carried out, the concrete cross section is reduced because of the detachment of the concrete cover and the reduction of reinforcement area further continues. It has been calculated that, due to the corrosion consequences, the cross section design resistant moment M_{Rd} reduces from 1,216 kNm to 902 kNm in the M-N interaction diagrams which anyway keep their symmetry within the time. Then, the dynamic behaviour of the structure has been further assessed, hypothesizing the worst scenario in which all the pillars are subject to isotropic degradation. This represents the most dangerous scheme since in the reality there are sides of the pillars that could be more protected against the deterioration, simply because of their location and the cladding in the actual structure,. In general, it can be commented that a redistribution of the actions and a top column deflection not higher than 7.17 mm have been calculated. The latter is anyway within the limits allowed by the current codes which correspond, for a structure like the one here assessed, to a maximum value of 25.7 mm. Moreover, also a non-linear pushover analysis has

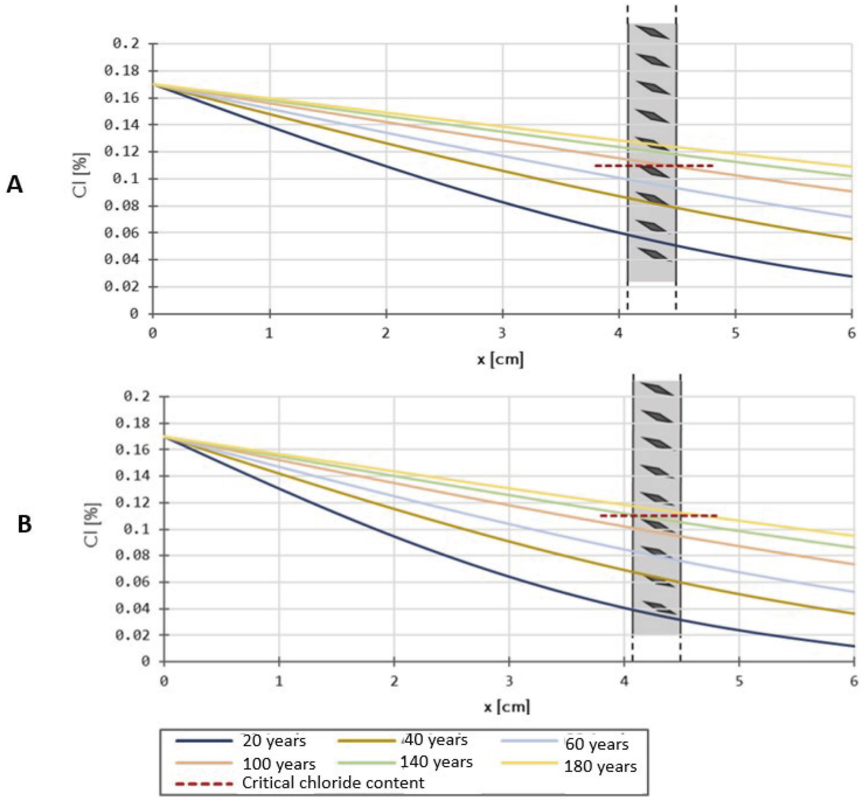

Figure 5. Calculated chlorides content at different ages for different depths for P_ORC (A) and P_CA (B).

been carried out with the consequent observation that plastic hinges form in correspondence of the edge of the pillars instead of along the beams. This is due to the design of the structure as a non-dissipative one. Nevertheless, the analysis demonstrated that the reduction of the cross section of the pillars doesn't cause any relevant changes in terms of structural resistance.

3 LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST

3.1 *The system boundary of the analysis*

A cradle to grave system boundary has been employed to develop the LCA taking into consideration a SL of 100 years in total and supposing the need of one maintenance activity at 52 years only for the case of P_ORC. This is due to the carbonation that, based on the results of experiments, turned out to be the most severe degradation phenomenon for the case here assessed. The hypothesized maintenance activities consisted in the removal of the damaged concrete cover and reinforcement bars with the substitution of the latter and the casting of a new layer for the concrete cover after having applied a primer to favor its adhesion to the substrate. Ten impact indicators have been employed in total to describe the outcomes of the analysis according to the 10 CML IA impact method which aims to describe the overall consequences on a local, regional and global scale. More in detail, the following impact categories have been accounted for the scope of this analysis: global warming (GWP); acidification (AP); ozone depletion (ODP); photochemical oxidation (POCP); eutrophication (EP); abiotic depletion potential (ADP); human toxicity potential (HTP); freshwater aquatic ecotoxicity potential (FAETP); marine aquatic ecotoxicity (MAETP) and terrestrial ecotoxicity potential (TETP).

3.2 *LCA and LCC outcomes*

The LCA analysis highlighted a relevant reduction of the impacts of P_CA compared to P_ORC up to 40% as for HTP, FAETP and TETP. This is mainly due to the complete absence of the maintenance activities within the predefined SL for the case of P_CA. In this regard it must also be highlighted that all the steel scraps generated because of the maintenance activities of P_ORC are accounted as recycled, representing an environmental benefit, and for this reason are numerically counted with a negative value. If that were not the case, the reduction of the impacts of P_CA in comparison to P_ORC would have been even higher. In general, cement has a relevant contribution to some impact indicators as 45 % for GWP for both P_ORC and P_CA. Such percentage value is even higher in the case of MAETP impacts of reinforcement, with a value equal to 98% for P_ORC. Moreover, the effect of reinforcement on the overall impacts is smaller in the case of P_CA due to the fact that no replacement of the steel bars is supposed for the latter. Figure 6 presents some results in this regard.

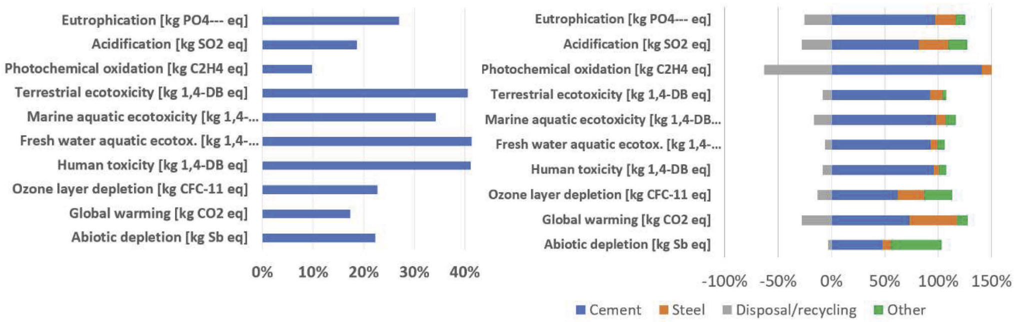

Figure 6. Impacts reduction of P_CA relative to P_ORC (left) and indication of the incidence of the main components on the overall impacts for P_ORC.

4 CONCLUSIONS

This research aimed to quantify the sustainability of a structure defined as strategic for the urban metropolitan area, comparing an ordinary technological solution to a self-healing one. To this purpose, the seismic resistance has also been checked after the appearance of a consistent degradation at the age of 52 years, because of the carbonation, for P_ORC. One of the first observations that can be made is that the use of CA for P_CA results in better durability parameters and hence longer predicted SL. In addition to this, the structural analysis demonstrated that the degradation mechanisms may affect the structural response but, for the case studied here, having been basically designed as non-dissipative, there is no significant problem though a reduction of the safety factor does actually occur. Moreover, the LCA outcomes, showing the consistent advantages of P_CA in comparison to P_ORC, highlight their importance as a decision making tool. They allow to make an “a priori” evaluation of the potential sustainability already starting from the design phase, to improve, in the future, the economic and environmental efficiency of the case study.

ACKNOWLEDGEMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860006.

The authors thank Penetron Italia and the construction management team, responsible for the works execution of “Nuovo Impianto di Depurazione Area Centrale di Genova D.A.C”, for allowing us access to the construction site besides giving us the opportunity to cast the samples necessary for the laboratory tests.

REFERENCES

Szabó, L.; Hidalgo, I.; Ciscar, J.C.; Soria, A. CO2 emission trading within the European Union and Annex B countries: The cement industry case. Energy Policy 2006, 34, 72–87, doi:10.1016/j.enpol.2004.06.003.

Turner, L.K.; Collins, F.G. Carbon dioxide equivalent (CO2) emissions: A comparison between geopolymer and OPC cement concrete. Constr. Build. Mater. 2013, 43, 125–130, doi:10.1016/j.conbuildmat.2013.01.023.

Ouellet-Plamondon, C.; Habert, G. Life cycle assessment (LCA) of alkali-activated cements and concretes; 2015; ISBN 9781782422884.

McLellan, B.C.; Williams, R.P.; Lay, J.; Van Riessen, A.; Corder, G.D. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. J. Clean. Prod. 2011, 19, 1080–1090, doi:10.1016/j.jclepro.2011.02.010.

Kumanayake, R.; Luo, H. A tool for assessing life cycle CO_2 emissions of buildings in Sri Lanka. Build. Environ. 2018, 128, 272–286, doi:10.1016/j.buildenv.2017.11.042.

Huntzinger, D.N.; Eatmon, T.D. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. J. Clean. Prod. 2009, 17, 668–675, doi:10.1016/j.jclepro.2008.04.007.

Shields, Y., Van Mullem, T., De Belie, N., et al. "An investigation of suitable healing agents for vascular-based self-healing in cementitious materials," Sustainability (Switzerland), V. 13, No. 23, 2021.

di Summa, D., Tenório Filho, J. R., Snoeck, D., et al. "Environmental and economic sustainability of crack mitigation in reinforced concrete with SuperAbsorbent polymers (SAPs)," Journal of Cleaner Production, V. 358, 2022.

Van den Heede, P., De Belie, N., Pittau, F., et al. "Life cycle assessment of self-healing engineered cementitious composite (SH-ECC) used for the rehabilitation of bridges." Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision - Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018. 2019. pp. 2269–75.

Cappellesso, V., di Summa, D., Pourhaji, P., et al. "A review of the efficiency of self-healing concrete technologies for durable and sustainable concrete under realistic conditions," International Materials Reviews, 2023, pp. 1–48.

Bertolini, L., and Pedeferri, P. "Tecnologia dei materiali. Leganti e calcestruzzo," Torino, Citta studi edizioni, 1996.

de Alcantara, N., da Silva, F., Guimarães, M., et al. "Corrosion Assessment of Steel Bars Used in Reinforced Concrete Structures by Means of Eddy Current Testing," Sensors, V. 16, No. 1, 2015, p. 15.

El Maaddawy, T., and Soudki, K. "A model for prediction of time from corrosion initiation to corrosion cracking," Cement and Concrete Composites, V. 29, No. 3, 2007, pp. 168–75.

Kannikachalam, N.P., di Summa, D., Borg, R.P., Cuenca, E., Parpanesi, M., De Belie, N., and Ferrara, L. Assessment of sustainability and self-healing performances of Recycled Ultra-High Performance Concrete (R-UHPC). ACI Materials Journal, 2023.

Stipanovic Oslakovic, I., Bjegovic, D., and Mikulic, D. "Evaluation of service life design models on concrete structures exposed to marine environment," Materials and Structures/Materiaux et Constructions, V. 43, No. 10, 2010, pp. 1397–412.

Wang, X.-H., Hu, D.-G., Hong, A. K. B., et al. "Prediction of Equivalent Chloride Ion Diffusion Coefficient in Cracked Concrete of the in-Service RC Element," KSCE Journal of Civil Engineering, V. 26, No. 5, 2022, pp. 2369–80.

Al Obaidi, S., Bamonte, P., Animato, F., Lo Monte, F., Mazzantini, I., Luchini, M., Scalari, S. and Ferrara, L.: "Innovative Design Concept of Cooling Water Tanks/Basins in Geothermal Power Plants using Ultra High Performance Fiber Reinforced Concrete with Enhanced Durability", *MDPI Sustainability*, *13(17)*, 2021, pp., 1–26, http://doi.org/10.3390/su13179826