Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)
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How to better exploit the use of LCA analysis for Ultra High Performance Concrete (UHPC) through a constitutive law which integrates chloride and sulfate attack

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ABSTRACT: Structural applications of advanced cementitious materials such as Ultra High Performance Concrete (UHPC) have been already assessed in harsh exposure conditions with presence of chlorides or sulfates. Nevertheless, the limited availability of design standards has not favoured so far a widespread use of these materials. Moreover, previous studies employed a constitutive model only partially representative of the real behavior of such materials when exposed to aggressive conditions. Therefore, this work, employing a "scenario dependent" constitutive law, estimates the serviceability limit state in correspondence of which it is needed to carry out the maintenance activities and investigates, through the Life Cycle Assessment (LCA) methodology, the ecological and economic profile of a UHPC water basin structure subjected to chloride and sulfate attack. The CML impact assessment method has been employed for the specific purpose to compare such structure to one made with ordinary reinforced concrete (ORC) using as system boundary the A1-B7 stages indicated in EN 15804.

1 INTRODUCTION

The construction sector, due to its social and economic impacts in the modern society (e.g. 9% of the gross domestic product of European Union and 18 million of people employed), requires a particular attention to be paid to its overall sustainability (Ortiz et al, 2009) (Oloke et al., 2022). The latter should encompass, from a holistic point of view, environmental, economic and social aspects. This challenge may represent an opportunity for the involved supply chain that has to be, then, rethought within a more sustainable framework starting from the extraction of the single constituent raw materials until the dismantling/recycling of the final product or structure. This means that also the design process of structures/infrastructures has to be based on a Life Cycle Assessment (LCA) approach to predict the future environmental and economic performances of a specific solution in comparison to another. Thus, the designers must be helped to also account the needs of the final users (long durability, reduced maintenance costs, adequate environmental performances) within the intended Service Life (SL). This is also in line with the path outlined by the European Commission action plan adopted in 2020 to favour a transition from linear towards circular production and consumption models. The latter represent a driving force to turn, what has been so far considered as a waste product,

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into a secondary raw material and keep (even if modified) its value in the economy as long as possible (European Commission, 2020). These concepts can then be transferred to the design of concrete structures employing a methodology such as the Durability Assessment Based Design (DAD) especially for advanced cementitious based materials such as the Ultra High Performance Concrete (UHPC) accounting for, "a priori", the interaction of the material with the surrounding environment (Kannikachalam et al., 2022) (di Summa et al., 2022) (Al-Obaidi et al., 2021) (Al-Obaidi et al.2022). This approach can overcome the limitations of the current standards that simply provide prescriptions, such as minimum cement content and maximum water to cement ratio, aimed at implicitly guaranteeing a target service life without considering the evolution of the behavior of the material over time, within the life span of the structure and as a function of its service scenario. In this framework, this work presents as case study a water basin structure aimed to contain geothermal water, characterized by the presence of sulphate and chloride ions. Different degradation phenomena have been taken into consideration, including sulphate attack, leaching and chloride penetration. Then, LCA and Life Cycle Cost (LCC) analysis have been carried out to investigate the potential sustainability of such construction technology in comparison to an ordinary reinforced concrete based solution.

2 DESCRIPTION OF THE CASE STUDY AND DEGRADATION MECHANISMS

2.1 *Description of the case study*

The analysis has been carried out assessing the case study of a basin aimed at containing the geothermal water coming from the condensation of the vapor extracted from the soil and cooled in a cooling tower and designed for a target service life of 50 years. The structure is 18 m long and 5 m wide, with a height of the compartment walls varying from 3 m up to 4.87 m, depending on the boundary morphological conditions since the structure itself is designed to be partially underground. Two different structural solutions are compared, characterized by two different design philosophies due to the different performance of the employed construction material. In the first scenario, the basin is built with ordinary reinforced concrete (ORC), including steel bars while the second design uses UHPC. They are hereinafter referred as ORC_basin and UHPC_basin, respectively. The mix designs for both cases are reported in Table 1. Figure 1 details the cross section of the vertical elements of both solutions. As it is possible to observe, the structural performance of UHPC (such as its compressive and tensile strength that can reach values around 150 MPa and 10 MPa respectively, much higher than the one of ORC) allowed to shift from the 0.4 m thickness of the ORC_basin to the 0.05 m thick UHPC_basin walls designed as supported by ORC buttresses. Similarly to other works (di Summa et al., 2022) (Kannikachalam et al., 2022) while the first implies the use of reinforcement bars (details shown in Figure 1), the second one has been designed as UHPC slabs supported by 2 m spaced reinforced ORC buttresses, without any reinforcement bars in the slabs. The latter was possible

Table 1. Mix design for ORC_basin and UHPC_basin.

Constituents [kg/m³]	ORC	UHPC
CEM I 42.5 R	350	-
CEM 52.5 R	-	600
Slag	500	-
Water	207	200
Aggregate 7/12	600	-
Aggregate 4/7	300	-
Sand (0-2 mm)	950	982
Limestone filler	60	-
Superplasticizer	-	33
Steel fibers	-	120
Crystalline admixture	-	4.8

employing, within the model code 2010 (Fédération internationale du béton, 2012), the mechanical properties of UHPC identified in (Lo Monte and Ferrara, 2020) and (Davolio et al., 2022).

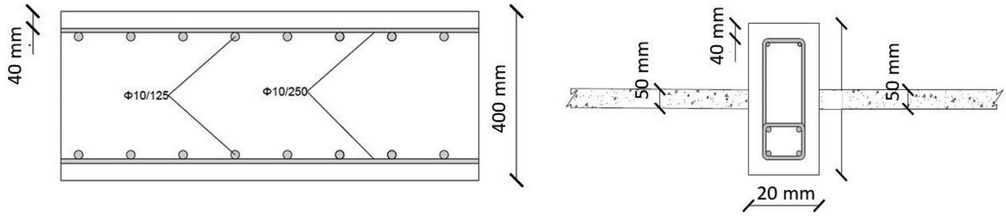

Figure 1. Cross section of ORC_basin (left) and UHPC_basin (right).

2.2 *Sulphate attack*

The sulphates penetrate into the concrete matrix reacting with the hydration products and causing expansion phenomena which have been here accounted according to the study by Jian et al. (Jian et al., 2018). The latter assessed the behavior of 54 mix designs defining in total three macro groups characterized by different expansion kinetics due to the chemical composition of the cement. Due to its mix design, the ORC_basin belongs to the group characterized by an expansion (EXP) as reported in Equation 1 while the UHPC_basin follows Equation 2, where C_3A is the C_3A cement content expressed in percentage (7.6% for the case of this study), T the time and w/c the water to cement ratio. In both cases, for this type of damage, the ultimate limit state has been defined by the attainment of an expansion ratio equal to 0.5% which is calculated to be reached, for the case of ORC_basin after 38 years and which is even not reached at 100 years for the UHPC_basin as detailed in Figure 2.

$$EXP = 0.0293\left(\frac{W}{C} * T\right) + 0.000975(C_3A) * T + 0.0216 \tag{1}$$

$$EXP = 0.0157\left(\frac{W}{C} * T\right) + 0.0305 \tag{2}$$

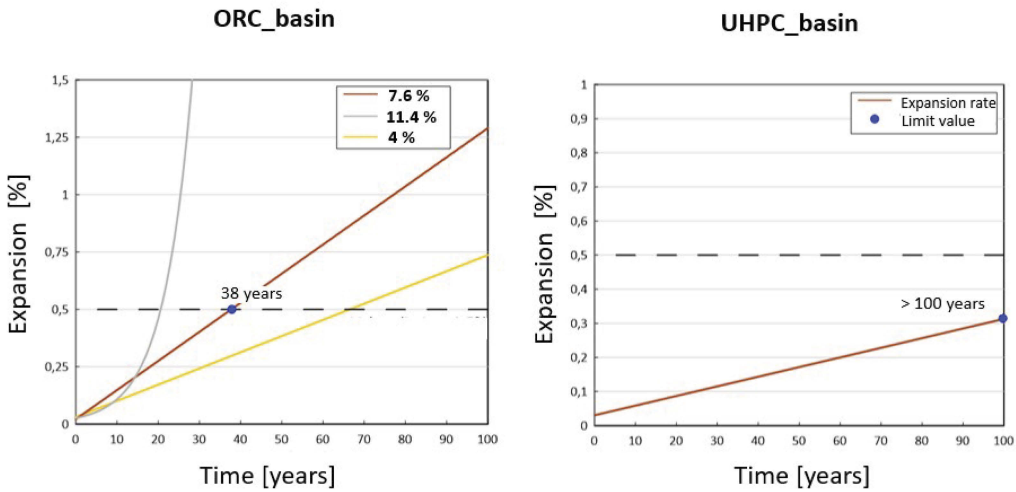

Figure 2. Expansion within a timeframe of 100 years. The graphs referring to the ORC_basin also contain the behaviour that the material would have had in the case of a C_3A content: 7.6%, 11.4 % and 4%.

2.3 *Leaching phenomena*

The $Ca(OH)_2$ leaching phenomena are mainly dictated by the permeability of the material itself and by the pressure of the water against the structure, with a consequent reduction of the cross section corresponding to the depth of the leached zone. Therefore, the process has been assessed according to Fagerlund (Fagerlund, 2021) according to Equation 3 where X corresponds to the depth of the leached area, t is the time, while a and k_e are the leaching coefficients considered as equal to 0.1385 mm/day$^{0.5}$ and 0 mm/day for ORC_basin and 0.0072 mm/day$^{0.5}$ and 0.006 mm/day for UHDC_basin respectively as in (Fagerlund, 2021).

$$X_{crit} = a\sqrt{t} + k_e * t \qquad (3)$$

Therefore, to identify the serviceability limit state for the case of this degradation mechanism, the time when the acting bending moment (M_{Ed}) is equal to the resistant bending moment (M_{Rd}) has been calculated according to the section which is reduced with time for each wall of the ORC_basin. It has been then estimated that for one of the walls of that structure, M_{Rd} and M_{Ed} are equal at 27 years. The same calculation has been performed for UHPC_basin where the limit is observed to be reached only after 58 years. In this regard it must be specified that M_{Ed} was calculated employing a cantilever scheme for ORC_basin while a plate analysis was adopted for UHPC_basin. Figure 3 reports the results above described.

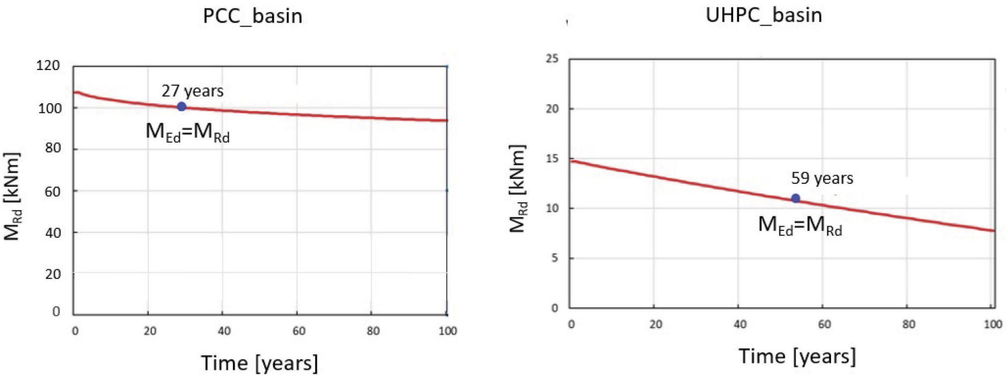

Figure 3. Variation of M_{Rd} according to the leaching phenomena for both ORC_basin and UHPC_basin within a timeframe of 100 years.

2.4 *Chloride penetration and steel corrosion*

The chloride penetration has been estimated employing the second Fick's law. With regard to ORC_basin both the initiation and propagation times have been estimated as in di Summa et al. (di Summa et al., 2022) and Van Belleghem (2018) obtaining a value lower than 6 months for the initiation. Then, considering for the propagation a localized damage such as a hemispherical pit, the serviceability limit state is assumed to be reached at the moment when 20% of the cross section is lost which is calculated to occur after 3 years for at least one of the walls of ORC_basin. This is in line with previous studies which demonstrated how 20% degree of corrosion can cause significant reduction in terms of strength capacity (Noh et al., 2018) (di Summa et al.,2022) (Bossio et al., 2017). With regard to UHPC_basin, other works already assessed case studies similar to the one here presented (di Summa et al.,2022) (Kannikachalam et al., 2022) but still employing a constitutive law not perfectly representative of the behaviour of the material when exposed to a chloride environment. Such studies considered the cross section, for the sake of simplicity, as progressively reduced along time accordingly to the chlorides penetration and supposed the steel fibers immediately corroded. In this respect, this study takes advantage of more recent studies (Davolio et al, 2022) (Al-Obaidi et al., 2022) where for the cross sectional equilibrium, the contribution of the region in tension affected by chlorides penetration follows a constitutive law as function of the crack opening and as function of time based on the experimental results and their extrapolation along time. This constitutive law has been obtained in (Davolio et al., 2021) who employed UHPC specimens characterized by the same mix design as the one here employed, and tested them in four point bending and direct tension after having subjected them to simultaneously acting sustained loads and exposure to either XA (acid) or XS (chloride) environment. Employing the constitutive law coming from both the aforesaid experimental campaign M_{Rd} always reaches the value of M_{Ed} after more than 100 years. Figure 4 better explains where the new constitutive law was employed also detailing M_{Rd} of UHP_basin within the time.

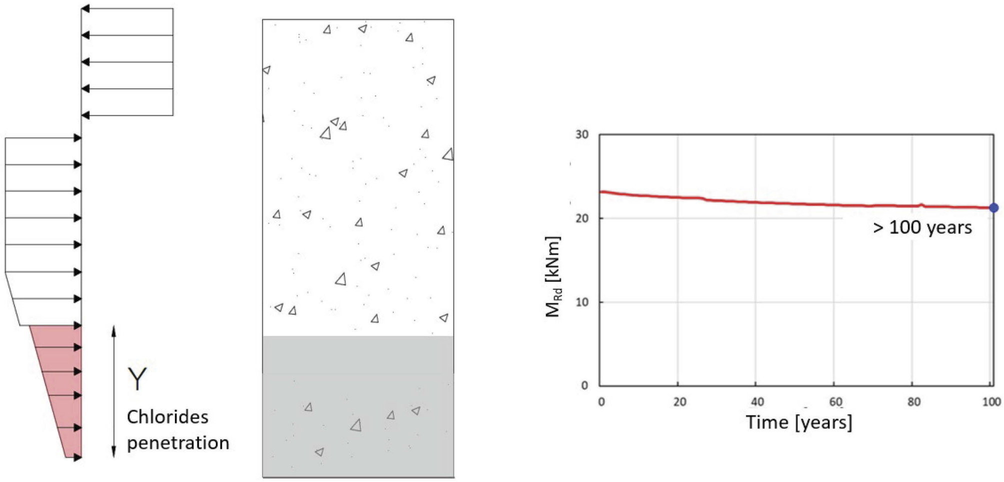

Figure 4. Representation of a generic UHPC cross section with the identification, in red, of the area affected by chlorides in which the new constitutive law can be used to better describe the behavior of the material (left) and M_{Rd} over time for UHPC basin (right).

3 LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST

3.1 *The system boundary of the analysis*

The LCA analysis has been carried out hypothesizing a cradle to grave system boundary in which the basin is considered as demolished at the end of its service life and treated as a waste material except for the steel scraps which are always considered as recycled according to the European regulations. The maintenance activity hypothesized for the ORC elements consisted in the removal of the damaged concrete cover and reinforcement bars, followed by the replacement of the latter and the realization of a new concrete layer after having applied a primer to favor its adhesion to the substrate. According to what has been stated in 2.2, 2.3 and 2.4, the most severe damage is represented by chloride attack, reason why one maintenance activity every 3 years has been considered for ORC_basin and for the ORC buttresses of UHPC_basin. No further repairing activities were calculated to be needed for UHPC_basin. The 10 CML IA impact method has been employed with the scope to describe all the implications at a global, regional and local scale. The LCC has been further developed according to the construction rates reported in (Regione Toscana, 2022) and (Regione Lombardia, 2022) referring to the Tuscany area, where the basin is supposed to be located. Moreover, a discount rate for the activities that have to be carried out in the future has been accounted for according to Caruso et al. (Caruso et al, 2020) and di Summa et al. (di Summa, 2022).

3.2 *LCA and LCC outcomes*

The environmental analysis demonstrated a consistent reduction for all of the ten impact indicators when the UHPC_basin is compared to the ORC_basin with advantages of around 80% as for the case of the terrestrial ecotoxicity and 70% as for the case of eutrophication, marine aquatic ecotoxicity, fresh water aquatic ecotoxicity and human toxicity. In general, it is possible to observe that cement and steel have the highest influence, reason why the impacts related to ORC_basin are so high, due to the raw materials needed to restore the functionality of the structure through the maintenance activities. More specifically, the greatest influence is represented by the steel for 6 out of 10 impact indicators of ORC_basin. On the opposite, UHPC_basin, due to the reduced amount of steel ($1.24*10^4$ *kg* in comparison to $3.39*10^4$ *kg* for ORC_basin) registers a higher influence of cement. With regard to the cost analysis, it has been calculated that the maintenance activities affect the overall costs of ORC_basin by about 39% while the overall difference between the two compared solutions is assessed at around of 37%. Figure 5 summarizes these results.

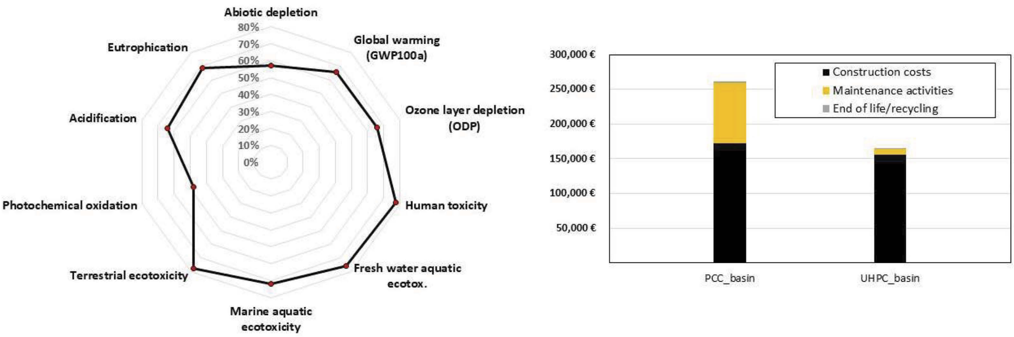

Figure 5. Percentage reduction of impacts of UHPC_basin compared to ORC_basin (left) and total costs within the SL (right).

4 CONCLUSIONS

This work has presented and assessed the implications of a design methodology aimed at including the use of advanced cementitious based materials with a structural design based on the durability of the material and on the life cycle implications, regarded as a pillar concept that should drive the construction sector within the near future. Differently from other recent works, the current study has analyzed not only the chloride penetration phenomena, but also the sulphate attack and the leaching degradation, due to the service scenario of the selected case study, consisting of a basin containing geothermal water. This approach, more structured than a prescription-based one which is normally employed whenever the current standards are simply followed, allowed to figure out the benefits of UHPC in comparison to a traditional solution, based on ordinary reinforced concrete, due to the total absence of maintenance activities for the first. In this regard, the Life Cycle Cost analysis has highlighted a relevant influence of the repairing activities whose reiteration for the ORC elements not only generates an increase of the total expenses but also the need to use more raw materials such as cement and steel whose environmental consequences are well known. Thus, this investigation represents a milestone to support and corroborate the efficacy of advanced cementitious materials even with the absence of the traditional reinforcement steel bars whenever aggressive structural service scenarios have to be met. These improvements are often disregarded in the current design and construction practice due to the false idea that a comparison between ordinary materials and innovative ones has to be based on a cubic meter scale, not taking advantage of durability and structural performance of the materials. This is also due to the absence of appropriate durability-based design approaches together with the further need to employ tailored, time- and scenario-dependent constitutive laws, which would require additional care in the design phase. In view of this, the DAD, together with LCA and LCC can be a driving force to shape differently the evolution of the construction sector.

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