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Sustainable concrete formulations for sustainable reinforced structures exposed to chloride induced corrosion

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Abstract. Reinforced concrete (RC) is the most used construction material for infrastructure due to its strength and durability. However, under chloride exposure, often the RC structures do not achieve their designed service life. Therefore, premature repairs or even replacement of components is required, hence increasing the environmental impacts and economic costs over the entire service life. This study evaluates the sustainability of low-clinker cements as a corrosion prevention measure in reinforced concrete under several chloride exposures conditions. Through a life cycle assessment (LCA), the environmental impacts of a RC generic element are evaluated, considering three alternatives for low-clinker cement and ordinary Portland cement as reference. The materials production and use service are considered in the LCA. The service phase includes the repair activities necessary to keep a defined level of serviceability given the steel corrosion due to chloride ingress. The number of repairs is determined on a probabilistic durability assessment. The results showed that the durability of the reinforced element plays a major role in the overall environmental impacts. Furthermore, low-clinker binders have a positive environmental impact in the sustainability of reinforced concrete structures.

1 Introduction

Reinforced concrete (RC) is currently the most important building material for infrastructure. However, the energy-intensive production of cement contributes significantly to the negative environmental footprint of the construction sector. The cement production is responsible for around 5% of all carbon dioxide emissions [1]. Therefore, there is a need to design reinforced concrete in the most sustainable way under consideration of the material production process and the requirements over the entire service life of a RC structure.

Frequently, the RC structures exposed to chlorides do not achieve their designed service life, in despite of complying the current prescriptive durability design rules. The chloride-induced corrosion reduces the RC service life, leading to premature repair measure that increases the carbon footprint of a RC structure even more [2]. One conventional approach for protecting the RC against chlorides is the addition of supplementary cementitious material (e.g. fly ash, slag, etc.) to the concrete mix design [3]. However, there is an increasing scarcity of some of those materials due to the reduction of coal composition and enhancement in the steel manufacturing processes [4]. Changes to the cement composition are unavoidable and alternative low-clinker, also named as low-CO_2 composite cements, are becoming increasingly important. However, there are still open question about their durability performance when exposed to harsh environments. The objective of the study is to evaluate the sustainability of low-clinker cements as a corrosion prevention measure in reinforced concrete under several chloride exposures conditions.

2 Methods

2.1 Life cycle assessment

The environmental impacts are evaluated using the Life Cycle Assessment (LCA) method following the standardized procedure in the ISO 14040 [5]. The functional unit is defined as a reinforced concrete plate with an area of 1 m^2 and thickness of 0.5 m with a service life of 100 years. The reinforcement density is assumed as 150 kg of steel per m^3 of concrete. The system boundaries include the materials production and service phase (Figure 1). The construction and end-of-life phases are assumed the same for each alternative, hence they are not included in this analysis. The manufacturing phase follows the cradle-to-gate approach including the extraction of the raw materials up to their processing. The service phase includes the repair activities necessary to keep a defined level of serviceability given the possibility of steel corrosion due to chloride ingress. In this study, only concrete patching is considered as a repair measure.

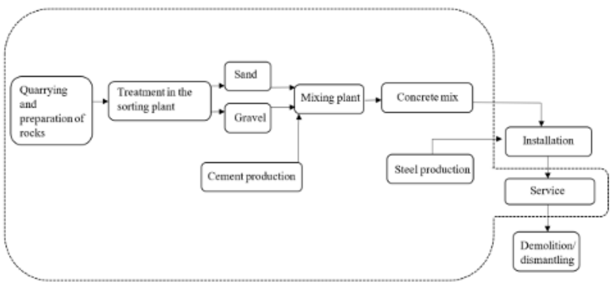

Fig. 1. System boundaries for the LCA.

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This study analyses 4 concrete mix designs, each of them having a different type of cement (see Table 1). Ordinary Portland cement (OPC) is taken as the reference or business as usual (BAU) scenario. All mixes had the same water/cement ratio of 0.40, as well as the same aggregates and admixtures. Minor adjustments of these last two were required to maintain workability properties. All mixed had a compressive strength at 28 days superior to 57 MPa. The reinforcement considered is regular carbon steel.

For the life cycle inventory, the input and outputs of each element were collected from several databases. The steels and cement information are taken from their Environmental Product Declaration (EPD), published in [6] by the German Institute for Building and Environment. Aggregates information derives from the ELCD-database [7]. The concrete patching impacts are taken from the results of the previous work by one of the authors [2]. Information regarding complementary elements such as water, energy and transportation were taken from the Ecoinvent database [8]. The midpoint indicators are Global Warming Potential (GWP) and Abiotic Depletion of Fossil Fuels (ADFF) are calculated using the method "CML-IA Baseline".

Table 1. Cement alternatives used in this study. * According to DIN 197.

Name	Cement type (*)	$D_{RCM,28}$ [$\cdot 10^{-12} m^2/s$]	α_{RCM}
OPC	CEM I 52.5N	5.34	0.3
CEM A	CEM II/B-S 42.5R	3.24	0.4
CEM B	CEM III/B 42.5L-LH/HS/NA	0.71	0.45
CEM C	-	0.0027	0.45

2.2. Service life prediction

In order to determine the number of repairs needed thorough the element service, a durability assessment was conducted applying a full probabilistic approach following [9]. The limit state is steel depassivation, which corresponds to the time when the chlorides (C) at the steel surface reach a critical threshold (C_{crit}). Equation 1 is used to calculate the chloride content at any time at the steel surface.

$$C(c,t) = C_o + (C_{S,\Delta x} - C_o) \cdot \left[1 - \text{erf}\left(\frac{c - \Delta x}{2 \cdot \sqrt{D_{app}(t) \cdot t}}\right)\right] \quad (1)$$

where: C(c,t) is time-dependent chloride concentration (wt.%/b) at the steel surface; C_0 is the initial chloride concentration (wt.%/b); $C_{s,\Delta x}$ is the chloride surface concentration (wt.%/b); Δx, depth of the convection zone (m); c, concrete cover (m); t, time (s); $D_{app}(t)$ the time dependent diffusion coefficient of concrete, which is calculated with equation 2.

$$D_{app}(t) = ke \cdot D_{RCM}(t_o) \cdot \left(\frac{t_o}{t}\right)^{\alpha RCM} \quad (2)$$

where: k_e is an environmental parameter to consider the ambient temperature [-], $D_{RCM}(t_0)$ is the chloride migration coefficient at the reference point [m²/s], α_{RCM} is the aging exponent.

Table 2. Input parameters for probabilistic modelling.

Parameter	Unit	Distribution	μ	σ
$D_{RCM}(t_0)$	10^{-12} m²/s	Normal	Table 1	0.2 μ
α_{RCM}	-	Beta (0,1)	Table 1	
t_0	Year	Constant	0.0767	
T	Year	Constant	100	
T_{ref}	°K	Constant	293	
T_{real}	°K	Normal	283	8
b_e	°K	Normal	4800	700
$C_{S,\Delta x}$	wt.-%/b	Lognormal		
Δx	mm	Beta (0,50)	10	5
C_{crit}	wt.-%/b	Lognormal	0.6	0.12
C_0	wt.-%/b	Constant	0	
c	mm	Normal	55	9

Table 2 shows the values used for the durability modelling. The temperatures correspond to the mean in Germany. Three chloride surface concentrations (Cs,Δx) were considered for this study with μ = 1.5, 3.5 and 5.5 [in wt.-%/b] and a COV of 75%. Those values correspond to low, high, and severe chloride environments, respectively. The execution of the concrete repair is set when the reliability index (β) reaches a limit value of 0.5 (depassivation probability of 30.9%). After the execution of repair, the element is assumed to return to its initial condition (t_0). Further details of this evaluation can be found in [10].

3 Results and discussion

3.1. Service life prediction

Figure 2 presents the results of the probabilistic modelling for the severe chloride condition ($C_{s,\Delta x}$ = 5.5 wt.-%/b). The CEM C had the best performance with a sustained reliability index (β) of around 4 over the 100 years. The CEM B also presented good results, with a β greater than 1.3 over the entire analyzed period. Therefore, these two cements should not require any repair measures over the entire analyzed period. The CEM A had the third best performance, here the β reaches at year 56 the limit value of 0.5, hence a repair at this point is needed. After that, the β finished with a value of 0.62 at year 100, which means no further repair is needed in order to meet the design service life. On the other hand, the ordinary Portland cement (OPC) had the worst durability performance. The β reached the limit value at year 13 thus meaning a repair. After restoring to the initial state, the degradation of the reliability index followed the same trend. A repair is needed every 13 years, meaning 7 repairs over the entire service life of 100 years.

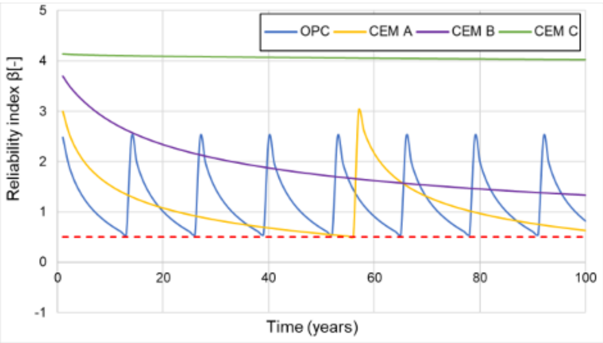

Fig. 2. Reliability index β vs time for $C_{s,\Delta x}$ = 5.5 wt.-%/b.

Figure 3 presents the results of the probabilistic modelling for the high chloride condition ($C_{s,\Delta x}$ = 3.5 wt.-%/b). Similarly, to the results presented in Figure 2, the CEM C experienced the best performance with a sustained β of around 4 over the 100 years. Followed by the cements B and A, which presented a β of 1.5 and 0.5 at the year 100, respectively. For these 3 cements no repairs are required since the β remained over the limit value of 0.5. The OPC experienced the worse performance, needing repairs every 22 years to meet the design service life of 100 years. The number of repairs is 4 for the OPC option.

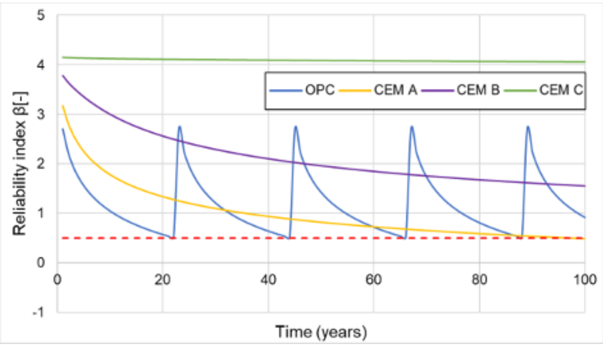

Fig. 3. Reliability index β vs time for $C_{s,\Delta x}$ = 3.5 wt.-%/b.

Finally, for the low chloride environment ($C_{s,\Delta x}$ = 1.5 wt.-%/b) are presented in Figure 4. Similar to the previous results, here the performance order of the analyzed binders is CEM C, CEM B, CEM A and OPC. Here is to notice that all the binder alternatives had reliability index greater than the established minimum (0.5), hence meeting the designed service life of 100 years.

The reason for the trends on the durability performance of the binders is due to their migration coefficients (D_{RCM}). In table 1 it is shown that the CEM C had the lower D_{RCM}, followed by CEM B, A and finally the OPC. Lower values for the coefficients represent a slower diffusion of the chloride ions into the concrete matrix. Thus, a greater time is required for the chlorides to accumulate over the steel surface and to trigger steel depassivation. Therefore, it is expected that for low values of the migration coefficient the degradation of the reinforced concrete in time is slower.

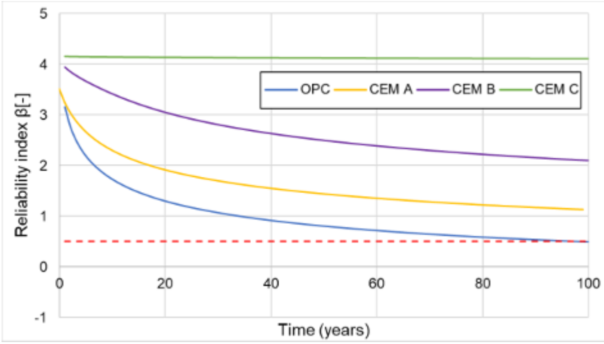

Fig. 4. Reliability index β vs time for $C_{s,\Delta x}$ = 1.5 wt.-%/b.

3.2. Life cycle assessment

Figure 5 presents the results of Global Warming Potential (GWP) for all exposure conditions and binder alternatives studied. The results of the GWP change drastically based on the analyzed exposure conditions. For the low surface chloride concentration (1.5 wt.-%/b), the CEM C presents greatest reduction of CO_2, with a value of -71% with respect to the reference (OPC). The CEM A and B also provided reduction in this analysis with -19% and -71%, respectively. In this scenario, the reduction of the GWP is mainly due to the reduced emission of the alternative binders A, B and C, which have a significant replacement in the clinker content following that order.

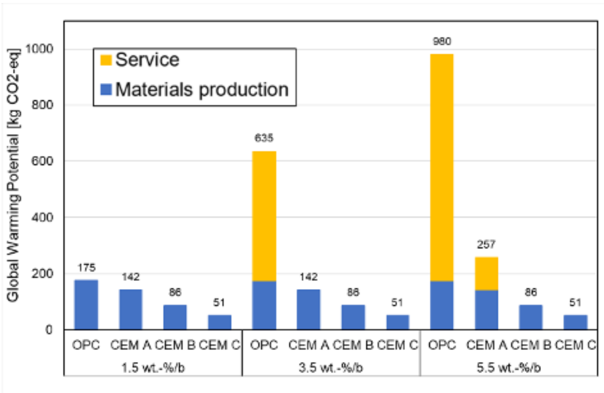

Fig. 5. Results of the global warming potential (GWP).

As the chloride conditions are more severe these reduction in the GWP is higher. For high surface chloride concentration (3.5 wt.-%/b) these reductions are -78%, -86% and -92% for CEM A, B and C respectively. Finally, in the most aggressive scenario (5.5 wt.-%/b) the reductions are -74%, -91% and -95% for the same binder order. The main reason for the enhancement in the GWP reductions is the service phase impact on the OPC alternatives. As shown in chapter 3.1, the OPC requires 4 and 7 maintenances within its service life for high and severe chloride concentrations, respectively. Those maintenance works, i.e. concrete patching, demands energy and raw materials, which results in a further emission of CO_2-eq (around 115 kg/m^2). The service phase accounts 72 and 82% of the total emissions for the high and aggressive emissions, respectively. In contrast, the binders CEM A, B and C require no maintenance for the high conditions, and only CEM A requires 1 maintenance for the most aggressive conditions. This implies a saving in the resources and energy consumption, translated here in the CO_2-eq.

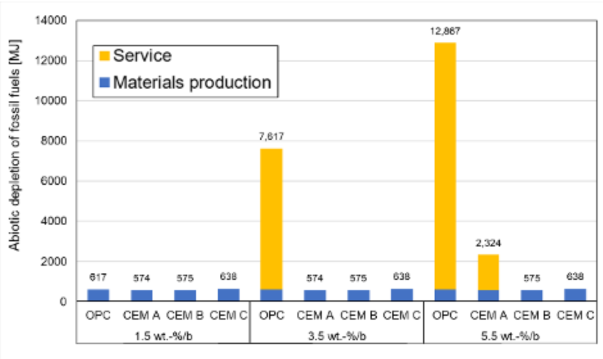

Fig. 6. Results of the abiotic depletion of fossil fuels (ADFF).

Figure 6 presents the results of abiotic depletion of fossil fuels (ADFF) for all exposure conditions and binder alternatives studied. Similarly, to the GWP, the ADFF results vary according to the exposure conditions. Nevertheless, here the ranking of the binder alternatives differs to that from the GWP. For the low surface chloride concentration (1.5 wt.-%/b), the CEM A and B presented a slight reduction of MJ, both with a value of -7% with respect to the reference (OPC). In contrast, the CEM C increased slightly this indicator in around 3%. On the other hand, for the more aggressive scenarios all the alternative binders decrease the ADFF indicators. For the high chloride concentration (3.5 wt.-%/b), the three alternatives reduced the indicator in -92% with respect to the OPC. In the most aggressive concentration (5.5 wt.-%/b), these reductions changed to -82%, -96% and -95% for CEM A, B and C, respectively. The service phase impact on the OPC alternatives also plays a fundamental role in the overall results of the ADFF indicator. The service phase accounted 92% and 95% of the total indicator for the high and severe chloride conditions. Hence, similarly to the GWP results, avoiding repairs within the service life of the element is provides a significant reduction on the ADFF indicator.

3.3. Sensitivity analysis

Due to the reduced offer of the low-clinker binders in the market, a sensitivity analysis is done to analyze the impact of extra transportation distance of these cements. The transportation is assumed to be by truck with a capacity of 32 Ton. The results of this analysis are shown in figure 7 for the GWP indicator. The reinforced concrete with CEM A would have to be transported 2,674 km to emit the same amount of kg CO_2 eq. as the OPC. For example, this would roughly correspond to the transport from Lisbon (Portugal) to Hamburg (Germany). The CEM B would have to be transported about 7,254 km, e.g., roughly from Dubai (United Arab Emirates) to Hamburg (Germany), to achieve comparable GWP results as the OPC. This distance is very unrealistic by truck, at this point ship transportation is preferred. Finally, for the CEM C, a transport distance of 10,180 km would be required so the GWP is the same as the OPC. This equivalent to driving from Seoul (South Korea) to Hamburg (Germany). Here is to notice that the service phase increase significantly the GWP indicator for the high and severe chloride conditions. Therefore, even if the alternatives binders are produced elsewhere far away from the production facility, they will still have significant reduction in the CO_2-eq emissions. Which are in the order of -72% and -82% for the high and severe conditions.

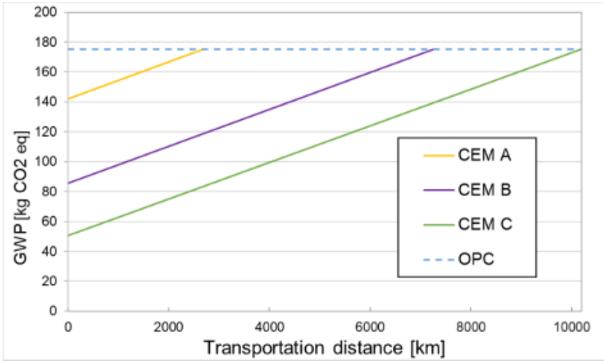

Fig. 7. Results of the sensitivity analysis for the transportation distance.

3 Conclusion and outlook

The objective of the study was to evaluate the sustainability of low-clinker cements as a corrosion prevention measure in reinforced concrete under to chloride exposure conditions. Based on the results of this study, the following conclusion can be drawn:

- The durability of the reinforced element plays a major role in the overall environmental impacts. The service phase accounts up to 82% of the total CO_2 emissions and up to 95% of the total abiotic depletion of fossil fuels.
- Low-clinker binders have a positive environmental impact in the sustainability of reinforced concrete structures. The alternatives binders provide a potential reduction up to 95% in both impact indicators.
- The positive impact of the low-clinker binders is significant even when there are large transportations distances (> 2000 km). Those reductions could be up to 72 and 82% for CO_2 emissions and ADPFF respectively.

The results of this study highlight the importance of the corrosion prevention for the sustainability of reinforced concrete structures exposed to harsh environments. Nevertheless, in this study only the environmental dimension of sustainability was assessed. Future works need to involve also the Economic and Social dimensions. Furthermore, there is also a need for analyze different maintenance schedules based on other limit states such as cracking or spalling. Finally, other prevention measures such as concrete cover variation, high alloys steel and cathodic prevention should also be addressed in future studies.

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