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Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks

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ABSTRACT

Chloride corrosion of reinforcing steel in concrete structures is a major issue in the construction sector due to economic and environmental reasons. Assuming different prevention strategies in aggressive marine environments results in extending the service life of the exposed structures, reducing the maintenance actions required throughout their operation stage. The aim of the present study is to analyze the environmental implications of several prevention strategies through a life cycle assessment using a prestressed bridge deck as a case study.

The environmental impacts of 15 prevention alternatives have been evaluated when applied to a real case of study, namely a bridge deck exposed to a chloride laden surrounding. The Eco-indicator 99 methodology has been adopted for the evaluation of the impacts. As some of the alternatives involve the use of by-products such as fly ash and silica fume, economic allocation has been assumed to evaluate their environmental impacts.

Results from the life cycle analysis show that the environmental impacts of the chloride exposed structure can be reduced significantly by considering specific preventive designs, such as adding silica fume to concrete, reducing its water to cement ratio or applying hydrophobic or sealant treatments to its surface. In such scenarios, the damage caused to the environment mainly due to maintenance operations and material consumption can be reduced up to a 30–40% of the life cycle impacts associated to a conventional design. The study shows how the application of life cycle assessment methodologies can be of interest to reduce the environmental impacts derived from the maintenance operations required by bridge decks subjected to aggressive chloride laden environments.

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1. Introduction

Great concern has arisen in the last decades on how human activities affect our environment in terms of climate change and depletion of natural resources, among other environmental consequences. This is especially so since the introduction of the sustainable development concept by the Brundtland Commission in 1987. The construction industry is one of the human activities that consumes more materials. It is also a carbon-intensive sector in our society (Ramesh et al., 2010; Shen et al., 2005), since it accounts for about 5% of the carbon emissions. Regarding production, concrete and other cement derivatives are the construction materials which most impact on the environment, since they are the most dominating materials used in this sector. As a result, over the past few years, there has been increasing interest in the environmental consequences associated to the use of such materials throughout the life cycle of different concrete structures, such as earth-retaining walls (Zastrow et al., 2017; Yepes et al., 2012), water storage tanks (Sanjuan-Delmás et al., 2015), utility poles (De Simone Souza et al., 2017) or building elements (Van den Heede and De Belie, 2014), among others. Besides the impact evaluation along the complete life cycle, it is also common to evaluate impacts derived from particular life cycle stages, such as concrete production (Braga et al., 2017; Texeira et al., 2016), both of them focusing either on specific environmental aspects, such as carbon emissions and embodied energy (Wang et al., 2012; Molina-Moreno et al., 2017), or on the use of score-based, standardized methodologies, such as ReCiPe or CML 2001

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(Gursel and Ostertag, 2016; Tait and Cheung, 2016; De Schepper et al., 2014).

In the context of sustainable design, special attention is paid to long lasting, concrete consuming structures, such as bridges (Du et al., 2014; Martínez-Martin et al., 2012; Penadés-Plà et al., 2016). Studies have been performed that deal with the bridge design optimization in terms of embodied energy (Martí et al., 2016) and in terms of greenhouse gas emissions derived from construction (García-Segura and Yepes, 2016; Yepes et al., 2015). However, less attention has been paid to the particular durability conditions of the structure and how the consequent maintenance needs during its life cycle affect the environmental evaluation of the design under a life cycle perspective (Pang et al., 2015; Zhang et al., 2016).

Degradation of reinforced concrete structures has been shown in recent years to be one of the most demanding challenges facing the construction industry (Gjørv, 2013). The poor durability of many concrete structures around the world derives in short structural service lives and this is not sustainable neither in economic nor in environmental terms (Gao and Wang, 2017). In addition, it is presently a common practice to deal with concrete deterioration mechanisms once the problem is detected and not before it arises. Such kind of strategy leads to greater impacts both in the economic and in the environmental field, since it is more material demanding in the long term than a sustainable design. Although there are several mechanisms that may degrade concrete in severe environments, like carbonation or sulphate attack, experience demonstrates that the most critical threat to concrete structures in marine environments is chloride-induced corrosion of the reinforcing steel bars (Costa and Appleton, 2001; Maes et al., 2012; Miyazato and Otsuki, 2010). Research has been carried out on this specific mechanism for many years, trying to understand the causes, reactions, and consequences of chlorides in concrete. This research has significantly improved our knowledge of the long-term behavior of reinforced concrete in chloride-laden environments. It has also led to the development of different preventive measures to increase resistance to corrosion from the very beginning of the structure life cycle, thus leading to less maintenance demanding solutions.

Focusing on the environmental consequences of concrete degradation of bridge structures, although maintenance is the main contributor to environmental degradation (García-Segura et al., 2014), few studies have been conducted on the environmental impacts that corrosion reducing design alternatives imply themselves. Mistry et al. (2016) compares the environmental performance of stainless steel versus carbon steel reinforcements in marine environments by using the CML 2001 methodology. Van den Heede et al. (2012) and Van den Heede et al. (2017) show how fly ash concrete performs better environmentally than conventional concrete under a life cycle perspective. Petcherdchoo (2015) evaluates the CO_2 emissions derived from bridge maintenance based on cover replacement of the existing concrete and on sealant surface treatments.

However, due to the fact that many contributions focus on the durability performance of single measures versus the performance of the conventional designs, the results existing in the literature do not meet the necessary conditions of comparability between alternatives: results should be based on the same functional unit, the evaluated system should include the same activities and processes, the same impacts should be assessed, and the same methodology for the impact evaluation should be used (Cooper, 2003). In this sense, this paper is devoted to assessing the environmental impacts that the different and most common corrosion preventive measures generate throughout the entire life cycle of a specific bridge deck, evaluating them under conditions of comparability. The different maintenance operations needed by each measure according to durability limitations have been taken into account. A real concrete bridge deck subject to a marine environment is taken for the study. This bridge deck is modelled and assessed by means of a life cycle assessment (LCA henceforth). This LCA is carried out according to the guidelines of the ISO 14040 and ISO 14044 series. Different preventive designs are considered in the analysis. These alternatives include the maintenance operations needed in each case during a considered period. The assessment calculates their respective contribution to the service life expectancy of the structure. The obtained service life estimates are used as LCA input to quantify the environmental impacts generated by each measure in the life cycle analyzed.

2. Materials and methods

2.1. Preventive designs and problem definition

The present analysis considers the three categories of preventive measures that are commonly used in the design of concrete structures in severe environments. The first category of measures relates to the characteristics of the concrete cover. This first category of measures increases the time needed by chloride ions to reach the embedded steel bars, which extends the service life of the structure. Two prevention subcategories have been considered in this group. The first subcategory implies increasing the concrete cover, thus increasing the distance to be travelled by chloride ions to reach the steel reinforcement bars. The second subcategory consists of increasing the coverage density by reducing the water/cement ratio of the concrete mix, thus decreasing its diffusion coefficient. A lower diffusion coefficient makes it more difficult for chloride ions to move through concrete, which results as well in more time needed for chloride ions to reach the steel bars. This latter subcategory also covers those cases where special additions are added to the concrete mixture in order to reduce the concrete porosity and so, again, its diffusion coefficient. Additions of fly ash, silica fume, and polymers are considered in the present study. The second category of measures modifies the composition of the reinforcing steel. Although both ordinary and prestressing steel bars are exposed to chloride corrosion, it is common practice to modify the ordinary steel composition, as it is usually more exposed to chlorides in bridge decks than the prestressing tendons. This second category of measures aims at extending the service life concrete structures by increasing the critical chloride content needed for the corrosion of the bars to be started. This is achieved by using corrosion resistant steels, such as stainless or galvanized steels. Both cases have been considered in this analysis. Finally, the third category of measures implies the isolation of concrete from the environment, thus preventing the access of chlorides to concrete by means of specific surface treatments. Two types of such treatments have been considered in the present analysis. Firstly, the impregnation of the concrete surface with a hydrophobic material and, secondly, the treatment with a sealant mortar mixture. There are other methods that prevent corrosion of the steel bars in concrete structures, such as the addition of corrosion inhibitors. These methods have not been considered in this study due to the uncertainties associated with the definition of the corrosion parameters needed to describe their performance (Bolzoni et al., 2014; Shi and Sun, 2013).

A unit length of a real concrete bridge deck exposed to marine chlorides is considered here to compare the environmental performance of alternative designs based on the aforementioned measures. The bridge of Illa de Arosa, in Galicia - Spain is considered as a case study. A cross section of the bridge deck is shown in Fig. 1. The input data regarding the durability and geometry

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