Construction and Building Materials 188 (2018) 391–398

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The influence of supplementary cementitious materials on climate impact of concrete bridges exposed to chlorides

Nadia Al-Ayish [a,*], Otto During [a], Katarina Malaga [a], Nelson Silva [a], Kjartan Gudmundsson [b]

[a] RISE, CBI Swedish Cement and Concrete Research Institute, Drottning Kristinas v. 26 114 28 Stockholm, Sweden
[b] Department of Civil and Architectural Engineering, Royal Institute of Technology (KTH), Brinellv. 23 10044 Stockholm, Sweden

HIGHLIGHTS

- LCA based on two service life models for chloride ingress was performed.
- A LCA based on a prescriptive approach may give misleading results.
- FA/GGBS lower the CO_2 emissions by cement replacement and service life extension.
- FA and GGBS may lead to lower owner, user and societal costs for bridge edge beams.

ARTICLE INFO

Article history:
Received 1 September 2017
Received in revised form 14 August 2018
Accepted 20 August 2018

Keywords:
Bridge
Chloride ingress
Climate impact
Corrosion
Durability
LCA
Service life
Supplementary cementitious materials (SCM)
Sustainability

ABSTRACT

In order to reach a specific service life of reinforced concrete structures a certain cover thickness is needed. At present, this is regulated by national standards that also limit the amount and type of supplementary cementitious materials in different exposure environments. The regulations do not, however, consider the actual durability performance of concrete with supplementary cementitious materials. As a consequence, the LCA results might be misleading. This paper shows the environmental impact of concrete with supplementary cementitious materials in chloride environment considering their specific performances. Prescriptive and performance based service life prediction models for chloride ingress are applied and compared.

1. Introduction

There is a need to reduce the climate impact of the built environment today and work towards a sustainable development. Alongside international and national regulations on target environmental improvements, the Swedish Transport Administration (STA) has set a vision to reduce the climate impact of infrastructures by 15% until 2020, 30% until 2025 and zero emissions by 2050, compared to levels from 2015. To reach this vision STA has since 2016 set a demand that all infrastructure projects with an investment cost above 50 million SEK (approximately 5 million euros) have to declare their climate impact [1]. And since concrete is the most common material used for construction of bridges in Sweden, optimisation of concrete will have a big role in reducing the environmental impact [2].

One way to reduce the environmental impact of concrete structures is to increase resource efficiency. Ordinary Portland cement (OPC) is the major contributor to the environmental impact of concrete and a decrease can be achieved by minimizing the proportion of OPC through the use of supplementary cementitious materials (SCM) from industrial by-products. Another climate gas reducing action is to make the construction more durable with a longer service life and less maintenance.

Chloride induced steel corrosion is one of the main durability problems of reinforced concrete (RC) structures in the world [3]. Due to the cold climate, the long costal line and the use of de-icing salts, frost- and chloride attacks are the most common durability

---

* Corresponding author.
E-mail address: nadia.al-ayish@ri.se (N. Al-Ayish).

https://doi.org/10.1016/j.conbuildmat.2018.08.132
0950-0618/

problems of RC structures in Sweden [4]. At present, the durability and service life of RC structures are mainly based on regulations which besides a minimum cover thickness also limit the use of SCMs in different exposure environments. Recent studies show, however, that this minimum cover thickness does not match reality and that SCMs should be taken into consideration as well [5].

The aim of this study is to evaluate the global warming potential (GWP) of RC structures considering the durability performance of SCMs according to new research. Five concrete mixes with different amounts of SCMs are applied in two cases, a bridge edge beam and a bridge pier, that are exposed to chloride environments. Life cycle assessment (LCA) is applied to evaluate the effect of the SCMs on service life and climate impact. Repair and replacement strategies that are used consider chloride induced corrosion as the only deterioration mechanism.

2. Sustainability of swedish concrete bridges

A study of 1170 bridges demolished between year 1990 and 2005 in Sweden showed that the majority of bridges were demolished between 30 and 79 year of age (85%) with a peak between 50 and 69 years (54%). The slab frame bridge, which is the most common type in Sweden, had an average age of 48 years. The main reasons for demolition were deterioration and low load-carrying capacity (72%) and rerouting (28%). It should be noted that the real service life for modern bridges will not be known until many years from now [6]. Throughout the years, a decrease in the water-cement ratio and an increase in the use of admixtures and SCMs are strongly linked to the durability [7,4].

Regarding life cycle costs (LCC) and maintenance, the bridge edge beam is of particular interest. A study by Racutanu showed that the edge beam system is one of the bridge parts that gets damaged the most and stands for 33% of all damages noted in a large sample of Swedish concrete bridges [4]. According to a study by Mattson the average age before replacing an edge beam is 45 years [6]. Also, based on historical statistics and personal communication with experts in this field, the life cycle measures (LCM) applied to an edge beam are: repair every 20 years, replacement every 60 years and impregnation every 20 years [8]. According to Veganzones et al. [9] bridge edge beams have high LCM costs and due to due to the traffic disturbance when repairing or replacing an edge beam there will also be user costs and societal costs. With this background the authors investigated the life cycle cost (LCC) of different bridge edge beam solutions regarding owner costs and user costs. They concluded that Life-cycle cost analysis (LCCA) is a tool for development of edge beam solutions and to evaluate different design alternatives. They also concluded that a low interest rate encourages an investment in better quality solutions that lowers the LCM costs. This is the case for stainless steel, where the investment costs were higher but the LCM and user costs were lower resulting in an overall lower LCC compared to an edge beam with regular steel. A similar LCC study was performed by During and Malaga [10] that considered the effect of low maintenance and hence low traffic disturbance. They showed that water-repellent impregnation of an edge beam can lower the user and societal costs and therefore the total costs considerably compared to replacement.

Several studies on LCA of bridges highlighted the importance of LCMs on the total environmental impact [11–14]. Durable materials and an effective LCM schedule may prolong the technical service life and thereby the environmental impact.

Müller et al. [15] suggest that the sustainability potential of a structure should be defined as the relationship between the lifetime performance and the environmental impact. According to this definition there are three approaches to enhance the sustainability: 1) lowering the environmental impact of the composition of concrete; 2) improving the concrete performance, i.e. reduction of cross-section of members through high load bearing capacity and 3) by optimizing the lifetime of the material and structure. Another study that considers the durability in LCA is Petcherdchoo [16] that investigated the effect of repairing concrete cover with fly ash (FA) concrete with regards to chloride ingress, service life and environmental impact. The author concluded that using FA in concrete repair in chloride environment lowers the climate impact not only due to lower clinker content but also because of the longer period between repairs.

Although researches have shown the link between environmental impact and durability there is still a lack of LCA studies that include the actual service life of structures with different concrete mixes.

3. Chloride ingress in concrete with SCM

The durability of steel reinforced concrete depends on the environmental exposures, the self-ageing of the concrete and the steel quality [17,18]. The steel reinforcement is protected from corrosion by a passivating film that is created due to the high alkalinity of the pore solution. As long as the pH is maintained high, the steel is protected against corrosion but as concrete is carbonated the pH in the pore solution drops, activating the corrosion process. However, carbonation is not the only corrosion inducing process. When chlorides penetrate the concrete and reach a certain concentration level, a so-called threshold value, an electrochemical process starts the corrosion of steel reinforcement, without the pH having to drop to a certain level. Chloride ions in the electrolyte can penetrate through the passive film to the metal surface due to the high potential difference across the film [19]. Other mechanisms for chloride ions to reach the steel surface are film breaking due to discontinuities in the film and adsorption of ions to the film leading to progressive thinning. It is the free chloride ions in the pore solution that react with the steel. It is, however, difficult to measure only the free ions and a total chloride content is therefore used when defining the chloride threshold value. The chloride threshold value includes, besides free chloride ions in the pore solution, chlorides which are bound chemically to the aluminate phase in the cement [20], and physically bound chlorides in the pore walls [21]. When incorporating SCMs in the concrete mix the material properties will change. Early studies have shown that adding fly ash or ground-granulated blast furnace slag (GGBS) to concrete will increase the risk of corrosion due to the lower alkalinity in the pore solution [22,23]. However, more recent studies have shown that fly ash and GGBS contain a higher amount of alumina which increases the chemical binding of chlorides [24,20], thus resulting in a higher chloride threshold value. Also, a denser microstructure has been observed in fly ash and GGBS concrete which lowers the chloride diffusion through the concrete [25]. The literature study of Shi et al. [26] showed that concrete with SCMs has an overall positive effect on the durability regarding chloride induced corrosion.

4. Service life prediction models

Durability means that the material is maintaining its technical performance under the designed service life. In ISO 16204:2012 “Durability - Service life design of concrete structures” [17] the design service life is defined by a definition of a relevant limit state, a number of years which the structure lasts, and a level of reliability for not passing the limit state. The design service life shall have an anticipated maintenance, but without a major repair being necessary. To verify the design service life ISO 16204 defines 4 methods with different levels of sophistication: full probabilistic, also called the DuraCrete model in Fib bulletin 34 – Model Code for