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LIFE CYCLE SUSTAINABILITY ASSESSMENT OF REINFORCED CONCRETE BRIDGES

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Abstract

Achieving sustainability in infrastructure requires a new design approach and implies an improvement of the standardized materials commonly used for the design and construction of structures. Environmental impact, which together with economic and social aspects is one of the three fundamental pillars of a holistically integrated definition of sustainability, is becoming an important factor in the requirements for designing sustainable structures. This paper gives a short summary of a research into state-of-the-art of life cycle sustainability assessment (LCSA) and their application to bridges, highlighting the phases of the life cycle and the methods employed. Considering that reinforced concrete is one of the most used materials for load-bearing elements of bridges and has a large application potential for all types and lengths of bridges, improving its sustainability is an important task. In that context, different types of concrete for structural use and the possible aspects of improving the sustainability of concrete mixes are discussed, including the “green” concrete.

Keywords: life cycle assessment, bridges, functional unit, green concrete, LCSA

1 Introduction

Over the past decade, numerous political decisions and guidelines have pursued the goal of implementing the principles of sustainable development in all areas of society and the economy. Thus, the European Green Deal [1] aims to achieve the sustainability of the European Union’s economy through the transition to a climate-neutral, environmentally sustainable and circular economy by 2050, and the goal of making Europe the first climate-neutral continent by 2050. The construction sector is one of the areas most responsible for the large amount of natural resources used [2], energy consumption and emissions into the atmosphere. The implementation of sustainable approaches in the construction sector is one of the most important sustainability goals.

2 Life cycle sustainability assessment (LCSA) methodology

2.1 Life cycle stages of civil engineering works and LCSA methods

Bridges have a long lifecycle and are subject to various new and more demanding requirements than those for which they were originally designed. The stages of the life cycle of civil engineering works are defined in HRN EN 17472:2022 [3]. Accordingly, the life cycle is divided into the following stages: A0 - pre-construction stage in terms of land and fees, A1-A3 material production stage, A4-A5 construction process stage, B1-B8 utilization stage and

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the end-of-life stage C1-C4. It is generally recognized that sustainability is based on the establishment of a balance between 3 main pillars, namely the ecological, the economic and the social. The methods developed to access each of the three pillars of the LCSA framework are Life cycle assessment (LCA), Life cycle cost (LCC) and (Social – Life cycle analysis) S-LCA. Based on a literature review, the paper [4] presents the current state of the art of LCSA and emphasizes that the most important point for a more reliable LCSA methodology is its harmonization, which allows comparability between studies.

2.2 Life cycle assessment - LCA

The LCA assesses the impact of a product, process or system on the environment during its life cycle. The LCA method is the most developed of the other two methods and has been the most widely used and studied in the last decade. The LCA is standardized in HRN EN ISO 14040:2008 [5] and HRN EN ISO 14044:2008+A1:2018+A2:2020 [6]. According to these standards, the LCA is not a sector-oriented assessment method, but provides general guidelines and assessment steps. A brief overview, description and discussion of LCA according to these standards can be found in the paper [7]. LCA consists of four phases: Goal and Scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. For LCI data, there are many databases that contain information on consumed resources and substances released into the environment during the life cycle of a product, process or system. In the LCIA phase, there are mid-point and end-point LCIA methods. The midpoint approach indicates the process or component with the highest contribution in the impact category, while the endpoint approach can provide an overall assessment of the bridge to the environment in terms of damage. In the Recipe [8] LCIA methodology, the endpoints of protection are damage to human health, damage to the ecosystem and damage to resource availability.

2.3 Life cycle cost - LCC

The aim of LCC is to find a long-term cost-efficient solution that takes into account a holistic, integrated methodology and evaluates all costs during the life cycle of the bridge. Paper [9] presents an overview a state-of-the-art of LCC analyses for concrete structures. During the long service life of bridges, LCC analyses are often carried out on the basis of net present value, where the discount rate plays an important role. In the life cycle of bridges, a distinction is made between agency costs and user costs. Agency costs include the costs of construction, maintenance, repairs during the use stage and demolition costs. User costs include the costs of travel delays, vehicle operating costs and accident costs. Due to the long service life of bridges, construction costs are often comparable to maintenance costs. Reduced maintenance reduces costs and emissions during the maintenance phase as well as traffic disruption and additional user costs due to congestion, overcrowding and longer detours.

2.4 Social-Life cycle analysis - S-LCA

S-LCA assesses the positive and negative impacts that a specific product, process or system has on society during its life cycle. A last version [10] of the guidelines for the implementation of the S-LCA was published in December 2020. Revision of the Methodological Sheets for Subcategories [11] in Social Life Cycle Assessment (S-LCA) were published in 2021. This document contains 40 methodological sheets divided into 6 categories of stakeholders: Workers, Local Communities, Value Chain Actors, Consumers, Society and Children. According to [12] the positive and negative effects of the S-LCA depend on the local conditions and the organization in the company, so that the social effects of identical production processes may be different in different regions.

3 Sustainability of reinforced concrete bridges

3.1 Conventional concrete vs. “green” concrete mixtures

Concrete is one of the most widely used materials for bridges worldwide due to its favourable mechanical properties and its robustness against exceptional weather conditions. However, as a structural material, concrete has many problems in terms of its global sustainability performance. The HRN EN 206:2021 [13] standard specifies the technical properties and other requirements for concrete placed in a concrete structure. It specifies various requirements, such as the permissible composition of the concrete and its proportions, the required properties of fresh and hardened concrete, the supply of fresh concrete, production control procedures, criteria and evaluation of conformity. In addition, the term k-value is defined, which specifies the permissible proportion of mineral admixtures (fly ash, silica fume and ground granulated blast furnace slag) in the components of the concrete mix. The challenge for the concrete industry is to produce “green” concretes that are not inferior to conventional concretes in terms of their mechanical properties, but have better sustainability performance. According to [14] the results of the environmental impact of concrete have shown that cement makes the largest contribution to the LCA and is responsible for around 90% of the environmental impact, followed by sand, gravel and admixtures. “Green” concrete is often developed in one of two ways or a combination of both: Reducing the amount of cement or reducing the use of natural aggregates. In the development of “green” concrete mixes, the use of nus-products as a substitute for a certain amount of cement in the production process is common. The use of natural aggregates is reduced by using recycled aggregates as a substitute for natural aggregates in concrete production. The standard for concrete HRN EN 206:2021 [13] Annex E and HRN EN 13369:2023 [15] for precast concrete products contain recommendations for the use of coarse recycled aggregates in concrete. The article [16] gives an overview of the LCA of concrete with recycled aggregates and highlights the existing problems in the LCA analysis of recycled aggregate concrete (RAC). The article [17] emphasizes the importance of using waste in the development and production of concrete mixes to reduce disposal costs and environmental impact, as well as the utilization of nanoparticles to obtain high-performance “green” concrete. The environmental impact of ultra-high performance concrete (UHPC) is often influenced by its high cement content, which is more than twice as high as that of normal strength concrete [18]. The paper [19] proposes a new “green” UHPC in which the binders are improved by the addition of nanomaterials and chemical activators, resulting in a “green” UHPC with low environmental impact and a very low cement content. The study [20] compares conventional lightweight concrete (LWC) with LWC made by replacing natural aggregates with recycled plastic waste and partially replacing Portland cement with fly ash (FA). The results show that “green” LWC has a lower environmental impact, but a decrease in compressive strength was also observed, making the novel “green” LWC suitable for non-structural applications only. According to article [21] the most sustainable concretes have the highest compressive strength and the improved durability. Article also highlights the importance of locally available materials and the importance of including performance parameters in the LCA of concrete, such as strength and durability. The durability of reinforced concrete is primarily determined by the possibility of aggressive substances penetrating the concrete. When planning the durability of concrete structures, it is important to ensure the intended service life. This is achieved when the exposure class and the concrete cover complies with HRN EN 1992-1-1 [22] [23], the recommended quality of the concrete complies with HRN EN 206:2021 [13] and the concrete is properly placed, compacted and maintained in accordance with HRN EN 13670:2010 [24]. Studies have been carried out to determine whether it is possible to increase the amount of supplementary cementing materials (SCM) or recycled aggregates beyond the established limits or to use types of ingredients not specified in the standards without compromising the quality of the concrete. In this way, the concrete must be tested to ensure that it fulfils all the prescribed requirements in order to be used for construction purposes. The comparison of such a new "green" and conventional concrete in terms of sustainability performance raises many questions about the requirements to be met and the functional unit (FU) for their comparison.

3.2 Functional unit

The FU for comparing the environmental impacts of different materials for structural purposes is not precisely defined in the established standards for conducting LCA analyses. The uncertainties associated with defining the FU and studies conducted to compare "green" concrete mixes with conventional mixes based on different FU are a key problem for the development of the "green" concrete industry. Therefore, various examples of FU for comparing different concrete mixes can be found in research papers. The article [25] gives an overview of different comparative LCA of concrete mixtures and found the LCA studies which do not consider the same range of compressive strength and service life, those which consider the same range of compressive strength without considering equal service life, those that do not consider the same range of compressive strength but consider equal service life, and those with considering both the same range of strength and equal service life. In some papers, the authors were familiar with the problem of defining a FU and compare concrete mixtures with differently defined FU. The research paper [26] analysed 5 different concrete mixes, some with added RAC or fly ash, and considered two scenarios. Scenario 1 included only strength requirements and FU was 1 m^3, and scenario 2 included strength, serviceability and durability requirements and for some concrete mixes FU was assumed to be 1.1 m^3. Paper [27] presented a FU for the comparative purpose of LCA of different concrete mixes so that service life do not be ignored in the analysis and the FU is presented as the environmental impact of one cubic meter of concrete per year. The authors [28] discuss the FU of LCA analyses for comparative purposes in the construction sector and give a recommendation for FU of reinforced concrete and define it as: "1 m^3 of concrete normalized to the 28-day compressive strength and the Reference Service Life, which must include the exposure class, the specific concrete and the type and percentage of reinforcement". In [29], two approaches for the functional equivalence of concrete structures with different concrete mixtures were discussed and tested: Correction of the volume of the FU or normalization of the calculated environmental impact with the compressive strength and service life when the FU has the same volume. The article concludes that the approach of normalizing environmental impacts is not relevant in practice and that the FU for a comparative analysis should be a structure as a whole [29].

3.3 Life cycle sustainability assessment of reinforced concrete bridges

Some studies have already been conducted and show different results based on material level and case study level for sustainability performance. The paper [30] compares conventional concrete (CC) with UHPC concrete at the material level and at the case study level and concludes that UHPC has a higher environmental impact at the material level considering the FU 1 m^3, but at the case study level and when comparing two bridges (CC bridge and CC bridge enhanced with UHPC), the variant of the bridge with the UHPC is a more environmentally friendly solution. Additionally, paper [31] therefore examined the environmental impact of two comparable bridges, one made of standard concrete and the other of high-performance concrete (HPC). The results show that the HPC bridge is an environmentally friendly solution, regardless of the environmental impact observed and the geographical context. The paper also emphasises that increasing the mechanical strength of a concrete increases the environmental impact per m^3, but a smaller amount of concrete is needed for the same function.

The article [32] compares two highway bridges over their life cycle, one made of conventional concrete and one made of HPC with SCM, and concludes that the HPC bridge has a longer service life, lower life cycle costs for the authorities and users and a lower environmental impact.

4 Conclusion

Environmentally friendly design is a new challenge for civil engineers and bridge designers. The analysis of new concrete mixes, so-called “green” concrete, is more frequently applied in research at the material level, while research, especially comparative research based on case studies, is less represented. Sustainable concrete for a structural application must fulfil the parameters of durability, load-bearing capacity, serviceability and sustainability performance indicators and be considered from a life cycle perspective. In addition to the above parameters, the problem of defining the appropriate FU for comparison purposes is a key issue in the research community. Furthermore, in LCSA analysis of bridges there are a very large number of indicators, many of which are specific to a particular bridge case study such as the distance of the concrete plant from the construction site, any transportation distances associated with the required concrete components, the number of average vehicles per day, the purpose of the bridge and accordingly the associated loads, the exposure classes associated with durability issues and other specific local conditions. “Green” concrete for structural applications needs to be evaluated from a life cycle perspective, taking into account any related specific case study indicators and sustainability performance issues for the intended function in use. Future research will be based on investigating application of different “green” concrete mixtures at case study level compared to conventional concrete mixtures and identifying possible trade-offs between different mixtures through the LCSA method based on observed cases.

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