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SERVICE LIFE EXTENSION, NOVEL MATERIALS, AND CIRCULARITY FOR IMPROVED SUSTAINABILITY OF CONCRETE INFRASTRUCTURE

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Abstract

As the world's natural resources are being depleted and climate change is affecting the planet and its population, it is clear that a change towards sustainable, carbon- and climate-neutral and circular construction sector is necessary. This article addresses the challenge of addressing sustainability for concrete infrastructure, focusing both on service life extension for existing structures, reuse and circularity as principles, and the use of novel materials for new structures. By taking a broader look at the problem, this article argues that a broad range of solutions needs to be put into practice to achieve the sustainability goals for concrete infrastructure.

Keywords: Assessment, Circularity, CO_2 emissions, Reuse, Service life extension.

1. INTRODUCTION

In recent years, concrete infrastructure has been facing two major challenges. Existing structures are ageing, requiring service life extension or replacement (Lantsoght *et al*., 2022)[1]. New structures need to be designed in a way that is more sustainable, so that the transition of the construction sector to a sustainable, circular, and carbon- and climate-neutral model can be achieved. At the same time, existing concrete infrastructure is subjected to the effects of climate change, resulting in more rapid deterioration and thus reduced capacity, as well as increased extreme events, and cascading and compounding extreme events, which may change the critical loading conditions for infrastructure (Cervantes *et al*., 2025b)[2].

In general, infrastructure is considered as the system of public works of a country, state, or region. Infrastructure is crucial to the proper functioning of a country, city, society, or organization. In this context of concrete infrastructure, the focus is on bridges, with reference made to tunnels and navigation locks. Managing the existing infrastructure, as well as extending infrastructure in countries that are in development is a major task. The cost of maintaining the existing infrastructure in proper condition is high. The 2025 report card for America's infrastructure of ASCE estimates an investment of $9.1 trillion required to reach a state of good repair (ASCE, 2025)[3]. In various countries, the peak of construction of bridges occurred during the 1960s and 1970s, resulting in an ageing bridge stock (Reitsema *et al*., 2020)[4]. Ecuador, which has a younger road network, also struggles with the upkeep of its bridges, with the province of Carchi having 85% of its bridges in poor or fair condition (Cervantes *et al*., 2024b)[5].

To transition the concrete infrastructure to a sustainable model, various actions are necessary. This work proposes a combination of three actions: service life extension for existing infrastructure where possible and safe, reuse of elements of infrastructure that is taken out of service, and the development of novel structural materials for the design of new structures, and showcases how research carried out in the Netherlands over the past two decades and more recently also in Ecuador contributes to achieving these goals.

2. SERVICE LIFE EXTENSION

Service life can be considered as the estimated duration an object can have during which it correctly fulfils the function for which it has been created. Service life is often expressed as a function of hours, but for engineering works it is expressed in years. In terms of assessment, both reaching the serviceability limit state and ultimate limit state need to be avoided and considered in the analysis. Replacing all infrastructure that reaches the end of its originally devised service life is not feasible. Service life extension addresses and aims to balance four sustainable development goals of the United Nation: 9. industry, innovation and infrastructure, 11. sustainable cities and communities, 12. responsible consumption and production, and 13. climate action. Service life extension is not always possible and requires careful consideration to verify if an existing structure fulfills the safety and usage requirements.

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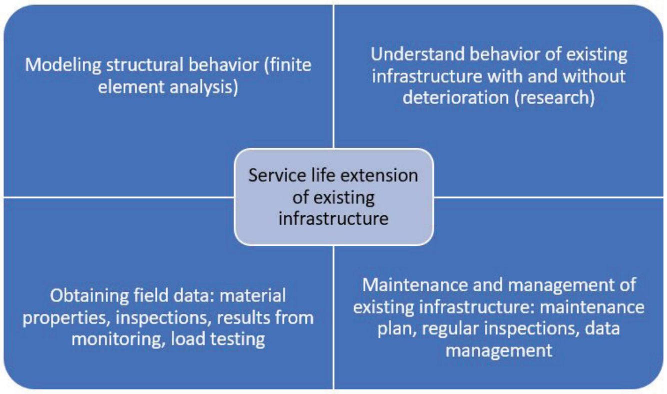

Figure 1: Strategy for service life extension of existing infrastructure

Figure 1 shows the combination of actions that can contribute to safe service life extension of existing concrete infrastructure. In terms of modeling structural behavior, it is important to understand the difference between the behavior of a structural element and the global structural behavior. For example, in post-tensioned slab-between-girder bridges, the overall behavior is determined by a combination of transverse load distribution, transverse load redistribution, compressive membrane action, and compressive arching action. This difference was investigated and made clear using collapse tests on a decommissioned bridge (Ensink *et al.*, in press)[6]. In addition, nonlinear finite element analysis was used to further understand the load-carrying mechanisms that occur in the overall structure (Ensink, 2024)[7]. For other bridge types, the distribution of the longitudinal moment, the contribution of non-structural elements, and the state of the bearings can determine the global structural behavior (Lantsoght, 2023a)[8].

Similarly, for the assessment and service life extension of land tunnels under fire loading, advanced non-linear finite element analyses that use a coupled and staggered thermo-mechanical approach have been used (Díaz *et al.*, 2024a; Díaz *et al.*, 2024b; Díaz *et al.*, 2024c)[9-11]. The approach combines assumptions for concrete spalling based on experimental evidence, the thermal-induced deformations of the structure, and the reduction of concrete and steel mechanical properties at high temperature, resulting from the temperature distribution in the concrete section. This temperature distribution is derived from the temperature load on the tunnel lining, which can be determined based on the fire source, via convection and radiation. The analysis is then carried out using nonlinear finite element analysis, combined with custom-developed numerical tools and the analysis includes both the heating and cooling phases of the fire (Lantsoght *et al.*, 2026)[12].

Secondly, research is necessary to understand better the fundamental behavior of concrete elements under shear (Lantsoght *et al.*, 2016)[13], punching (de Sousa *et al.*, 2023)[14], torsion (Valdivieso *et al.*, 2016)[15], and fatigue (Lantsoght *et al.*, 2019)[16], as well as the effect of deterioration on these failure mechanisms (Cervantes *et al.*, 2025b)[2]. In addition, most experimental work in the past has focused on rectangular, heavily reinforced, concrete beams, whereas other structural elements such as slabs, which display a large transverse distribution capacity (Lantsoght *et al.*, 2015)[17], have not been addressed similarly. Therefore, targeted experimental campaigns are necessary to better understand the failure mechanisms in realistic structural members, and to be able to transfer these insights to the practice of assessment of existing structures (Lantsoght *et al.*, 2017a)[18].

Thirdly, to assess the performance and condition, as well as structural safety of existing infrastructure, it is necessary to obtain field data (see Figure 2). The first step is always to carry out an inspection, which can be a quick visual inspection to get a first idea of the condition of the structure, as well as a broad inspection of structural elements and the surrounding areas to identify particular threats (Valenzuela *et al.*, in review)[19], potentially expanded with the use of material sampling such as core drilling, and non-destructive testing and evaluation methods (Cervantes *et al.*, 2024a; Cervantes *et al.*, 2025a)[20-21]. When it is necessary to check the performance of the structure under loading, a diagnostic load test can be carried out, and when a direct assessment is necessary, a proof load test can be used (Bertola *et al.*, 2025; Lantsoght *et al.*, 2017b; Lantsoght *et al.*, 2017c)[22-24]. The type of field data that needs to be obtained can be considered as a function of the state of information prior to the inspection, in terms of bridge documentation, material data, load testing data (if any), and traffic data (de Vries *et al.*, 2022)[25]. In addition, in terms of calculations for assessment, the concept of different levels of approximation, as first introduced in the 2010 ***fib*** Model Code (***fib***, 2012)[26], can be used to map the state of information to the types of assessment calculations that can be carried out. This approach has been fully mapped for the assessment of existing reinforced concrete slab bridges in the Netherlands (Lantsoght *et al.*, 2017a)[18].

Finally, the fourth and last aspect of the framework from Figure 1 is the management and maintenance of existing infrastructure. For this purpose, it is necessary to have a central data administration of bridges, which includes plans, inspection reports, as well as an evaluation of the current state of the bridge and the network corridors. An annual overall evaluation of the state of infrastructure in a country is a good way for decision-makers to see where investments need to be prioritized. Here, a large potential for digital twins can be identified, which is a topic of current research and development (Lantsoght *et al.*, in review)[27]. Moreover, using machine learning on field data, especially monitoring data, provides the possibility to forecast bridge performance (Lantsoght *et al.*, 2025)[28]. In general, for this purpose, digitalization of infrastructure information, at all stages of the life cycle, is necessary. Such

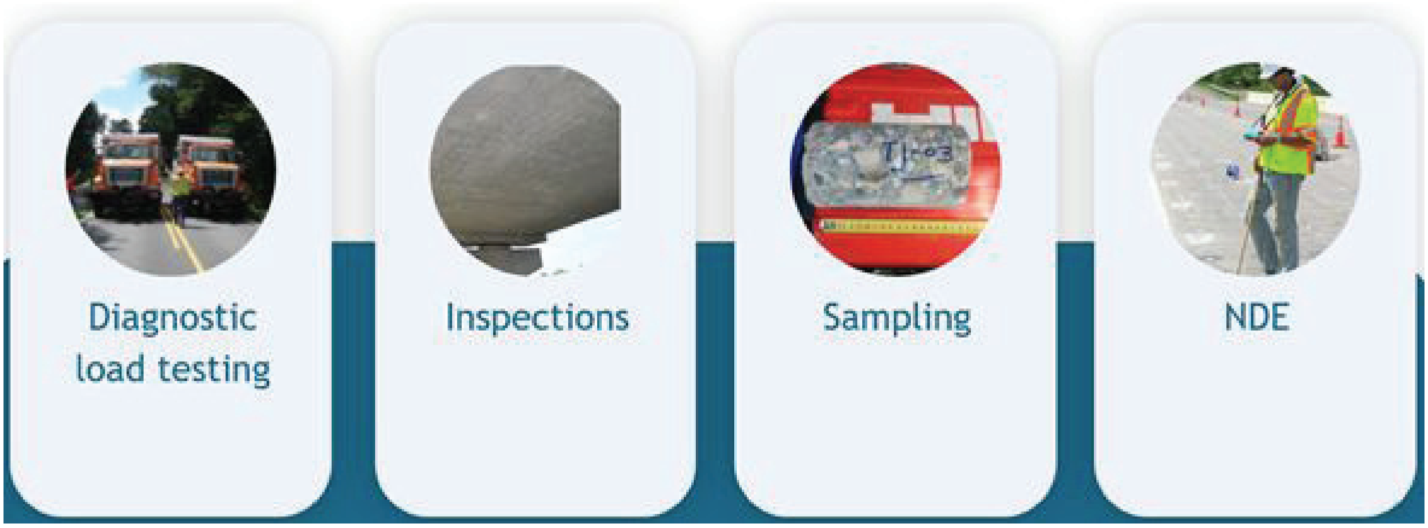

Figure 2: Methods of obtaining field data

methods have been developed for bridges, and are being developed for networks of navigation locks (van Sloten *et al.*, 2026)[29].

The sustainability impact of service life extension can be quantified. In the Netherlands, reinforced concrete solid slab bridges have a large presence in the road network, and many of these existing bridges do not fulfil the code requirements for shear upon assessment (Lantsoght *et al.*, 2017a)[18]. When advanced calculation methods can be used to demonstrate that the superstructure can still be used instead of needing replacement, or when code compliance can be demonstrated directly through a proof load test, the sustainability impact can be determined by comparing the option of replacing the superstructure by comparing the impact of the proof load test or by comparing to keeping the superstructure without changes.

The analysis looking at the use of advanced computation methods for a reinforced concrete slab bridge with end spans of 10 m and a mid span of 13 m, depth of 0.5 m and width of 19.2 m. The economic impact of replacement was estimated in 2013 (Lantsoght *et al.*, 2013)[30] as in the range of 500000 - 640000 €, the CO_2 impact was estimated between 136 tons for Portland cement concrete and 74 tons when using blast furnace cement, and the indirect social cost is a function of the location of the bridge and can be 8 to 9 times larger than the economic cost. Additionally, for the viaduct Zijlweg, the analysis quantified the superstructure replacement in comparison to the sustainability impact of a proof load test (Lantsoght, 2023b)[31]. The analysis showed that the economic cost would range between 264300 and 330400 €, the carbon footprint 109 tons CO_2 (with the different contributions as indicated in Figure 2), and the societal cost is estimated through driver delays, giving 833000 €. In comparison, the cost of the proof load test was 80000 € (including a research component), the test created 0.3 tCO_2 and closure of the bridge caused 11415 € in driver delays. The sustainability gains can thus be seen from comparing the replacement and the testing options.

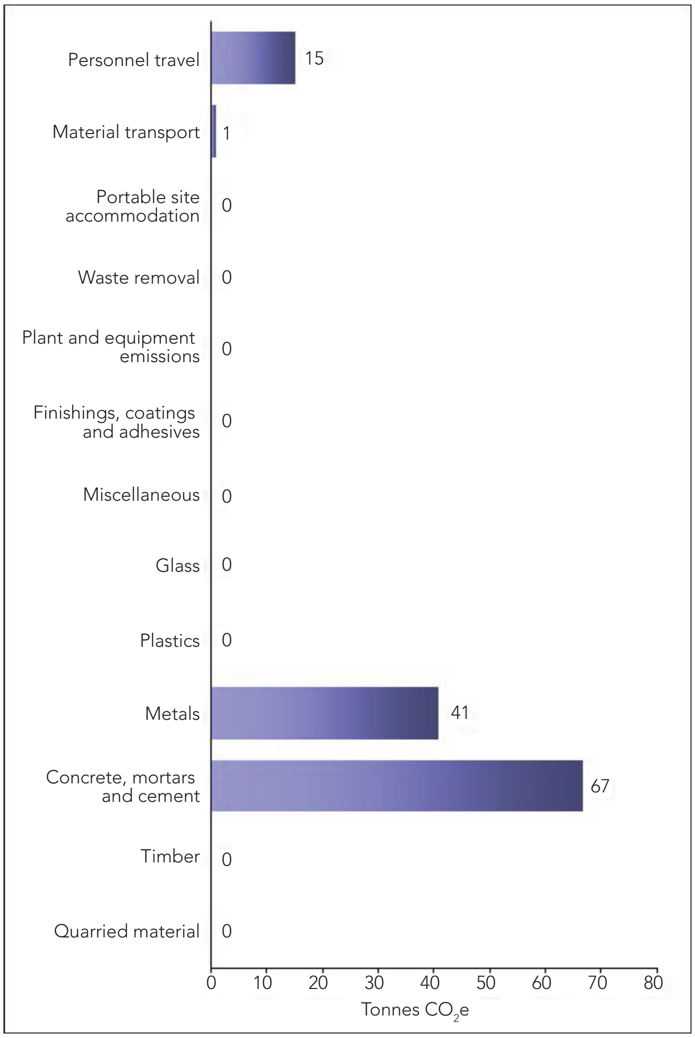

Figure 3: Breakdown of calculation of carbon footprint for superstructure replacement of viaduct Zijlweg (Lantsoght, 2023b)[31]

3. REUSE AND CIRCULARITY

Nowadays, reuse of concrete elements is often limited to the use of recycled aggregates (Játiva *et al.*, 2024)[32], and this approach is becoming standard practice to reduce the impact of construction demolition waste on the planet, as well as to reduce the use of rolled river or mined aggregates, as these practices contribute to the depletion of the planet's resources. However, in recent years, pioneering work has focused on the reuse of structural elements. Examples of this work include the design for circularity proposed by (Schrooten, 2020)[33] for buildings, where the idea of reuse centers around the reuse of modules of the building after dismantling the building. Similarly, pioneering work has focused on the reuse of bridge girders from decommissioned bridges in new bridges (Vergoossen *et al.*, 2021; Vergoossen *et al.*, 2023)[34-35]. The applications have focused on the use of prefabricated girders. Research has also explored the reuse of prefabricated box girders, showing large potential for the reuse of these structural elements as well (Haarsma, 2022)[36]. This discussion on reuse and circularity shows that reuse can occur both at the material level, using recycled aggregates, as well as at the structural element level. The carbon footprint reduction that can be achieved using recycled aggregates has been estimated to be up to 65% (Ma *et al.*, 2025) [37].

4. NOVEL MATERIALS

As Portland cement contributes to an estimated 5 to 8% of the world's annual CO_2 emissions (Pacheco-Torgal *et al.*, 2012)[38], alternatives are necessary to reach the objectives of developing carbon- and climate-neutral construction products. As mentioned before, a single replacement material should not be recommended. Instead, tailoring the concrete mix to the performance requirements will result in optimal material use. To achieve this goal, research that addresses the material level, sectional level, and structural element level needs to be carried out, as sketched in Figure 3.

In recent years, a broad variety of new concrete and concrete-like materials has been developed, such as ultra-high performance fiber reinforced concrete [UHPFRC (Bertola and Brühwiler, 2025)[39]], concrete using natural fibers (Castrillon *et al.*, 2025; Patel *et al.*, 2025)[40-41], strain-hardening cementitious composites (Luković *et al.*, 2014)[42], and alkali-activated concrete (Qian *et al.*, 2022)[43], to name a few. While most research has focused on developing these new materials, structural concrete researchers are now working on taking the next step, which is understanding how their structural performance differs from Portland cement concrete structures, which additional testing may be necessary, and, most importantly, how to best map structural performance needs to material properties, so that the optimal choices for materials can be made in new design projects, as well as for strengthening of existing structures.

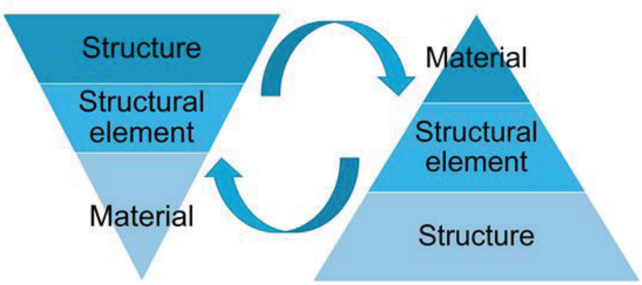

Figure 4: Need for innovation at multiple scales when applying novel materials

To apply natural fibers, for example, various steps need to be taken. At the material level, surface modification methods need to be developed to create better durability of the natural fibers in the alkaline concrete medium. Then, to be able to design cross-sections using concrete with natural fibers, constitutive equations have been derived based on flexural testing of prisms (Patel *et al.*, 2025)[41]. A next step will consist of testing reinforced concrete members that include natural fibers, where the flexural capacity will be validated, and methods for finding the shear capacity of fiber reinforced members can be extended to the application of natural fibers (Lantsoght, 2023c)[44].

The sustainability impact of using novel materials has been estimated by considering the carbon footprint of the materials. The carbon footprint of Portland cement concrete was estimated in a study as 509 kg/m^3 and compared to the footprint of alkali-activated concrete resulting in 122 kg/m^3 (Qian *et al.*, 2022)[43].

5. SUMMARY AND CONCLUSION

This paper gives a broad view on the various solutions that are necessary to achieve concrete infrastructure that is safe, performing well, and supporting society's needs, while at the same time fulfilling requirements for sustainability, circularity, and contributing to the transition to a carbon- and climate-neutral economy. The main message of the paper is that a broad portfolio of solutions is necessary to reach this goal, and that a single approach, such as using more sustainable alternatives for Portland cement, is too narrow to achieve the grand challenge at hand, see Figure 4. At the same time, international collaboration is crucial to address the challenges: global challenges need global solutions tailored to local conditions.

To achieve these goals, this paper argues that a wide range of solutions are necessary:

1. For existing infrastructure, service life extension can be considered if safety and performance requirements are fulfilled. To understand the structural safety of existing concrete infrastructure better, a combination of modeling techniques with a focus on the global structural behavior,

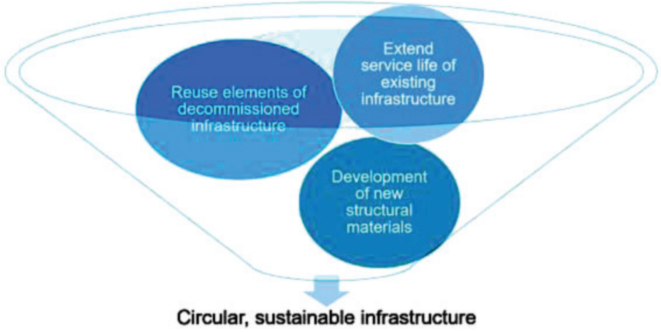

Figure 5: Combination of solutions to achieve circular, sustainable infrastructure

research to understand failure mechanisms with and without the effect of deterioration, field data collection methods, and improved maintenance and management is proposed.

2. When service life extension is not possible, and an infrastructure asset is decommissioned, then reuse of the structural elements should be considered. If reuse is not feasible, the breaking down of the concrete structure to provide recycled aggregates is a next possible step.

3. For the design of new structures in the future, a better combination of material and structural design needs to be achieved. With advances in concrete and concrete-like materials, it becomes possible to tailor the choice of the material to the demands of the structure and its location, so that optimal and cost-effective choices can be achieved.

Overall, the broad range of solutions that are already available nowadays for new and existing concrete infrastructure makes it feasible to achieve the necessary transition, but it will require creativity and a shift in choice of solutions to a broader variety of options tailored to each specific problem.

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