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# Choice of Sustainable and Durable Concrete Structure Using LCA

**A Horáková, I Broukalová and A Kohoutková**

Department of Concrete and Masonry Structures, Faculty of Civil Engineering, Czech Technical University in Prague

anna.horakova@fsv.cvut.cz

**Abstract.** The paper presents a new perspective on the issues of life cycle assessment (LCA) and durability analysis of structures. In the case study, a comparative analysis of three variants of the chosen structure was performed. Subsequently the durability of all variants was assessed. The structural solutions were modified to achieve a targeted life cycle for all variants. Modified structures were evaluated in LCA. The study points to the fact that orthodox compliance with code prescriptions can lead to an uneconomical and unsustainable solution and suggests an approach where the design of the structure is adjusted for the required service life.

## 1. Introduction

Sustainable construction issues are a new topic in the structural design. The aim is minimizing impacts of construction and operation of structures on the exploitation and pollution of the planet and on the increasing climate change. In the effort to minimize the impacts of concrete production, we should not only focus on reducing the environmental impact of concrete components, but also use common sense and engineering judgement and adhere to the following principles:

Correctly design the shape and supporting of the structure or the structural element, which corresponds with the stresses in the element. Based on the understanding of the material properties, use effectively its potential. Design the appropriate life cycle of the structure. The issue of the durability is closely related with the issues of sustainable construction. Buildings with adequate durability require fewer repairs during their existence. In the case of more durable buildings, it will take longer period to reach the stage, when demolition and construction of a new building are needed. The environmental impacts associated with construction are then offset by longer construction work without the necessary repairs.

Application of LCA tools to assess the construction impacts on the environment is known but we should go beyond the tool as it is used so far, and use it to optimize the structural design, improve the structural behaviour, and reduce the environmental burden.

In our study, the computing tools were applied to design an efficient structure and exploit the potential of an excellent material.

A case study was performed for chosen structure – a floor structure of a parking house with slab spanning 5.4 m supported by beams.

In the first phase of the study, a commonly used approach was applied. Material and structural solution were chosen, and a structural design was performed. Subsequently, the designed structures were analysed in LCA.



In the second phase, analysis of durability was used to adjust the structural design. For all structural variants a target life span was established, and the life cycle of the structures was analysed again.

## 2. Case study

Three variants of the floor structure were designed. The variants differ in strength class of concrete and thickness of concrete slab. The first variant (1) is from normal strength concrete (C35/45), the other variants (2A, 2B) are from high performance concrete (C90/105). In one case the mechanical properties of high-performance concrete were used to reduce the thickness of the slab (2A). In the other case these benefits were used to reduce the volume amount of steel (2B). The parameters of the variants and the concrete recipes are shown in the following table:

**Table 1.** The parameters of the variants

| Variant                                                              | 1      | 2A      | 2B      |
|----------------------------------------------------------------------|--------|---------|---------|
| Strength class of concrete                                           | C35/45 | C90/105 | C90/105 |
| Spacing of rebars [mm]                                               | 120    | 100     | 130     |
| Rebar diameter [mm]                                                  | 8      | 8       | 8       |
| Required area of reinforcement $A_{s,req}$ [mm <sup>2</sup> ]        | 408,0  | 486,7   | 384,4   |
| Provided area of reinforcement $A_{s,prov}$ [mm <sup>2</sup> ]       | 418,9  | 502,6   | 386,6   |
| Cover of reinforcement [mm]                                          | 50     | 45      | 45      |
| Distance of the centre of reinforcement and surface of the slab [mm] | 54     | 49      | 49      |
| Thickness of slab [mm]                                               | 180    | 140     | 180     |

Sustainability of the structure was evaluated by Life-cycle assessment (LCA) according to relevant standards. LCA is a method of assessing the environmental impact of a product, which is usually based on the entire life-cycle or at least on its significant part. Hence, the evaluation includes obtaining of raw materials, their transport to the place of processing, processing of raw materials, manufacturing of a final product, storage if necessary, use of the product and also maintenance or repairs if necessary, and finally removing the product, including the recycling of its parts. This assessment is known as “from cradle to grave” analysis. In some cases, the prediction of the course of the phase of use is not possible and the evaluation includes only the phases from obtaining of raw material until the time when the product leaves the factory (“from cradle to gate”) or until transporting the product to the place of use (“from cradle to site”). Within the assessment the most significant environmental impacts are considered, such as consumption of raw materials, global warming and climate change, acidification and eutrophication of the environment, depletion of stratospheric ozone and photooxidation. These environmental impacts are within the LCA method indicated as impact categories. Assessment of the designed variants is based on the part of life cycle: from obtaining of raw materials to manufacturing of a final product. So, the evaluation includes impacts associated with the manufacturing of concrete and steel, transport of these materials to the site of the building and transfer of these materials during the realization of the building. The following table shows the volume of concrete and the weight of steel for the designed variants:

**Table 2.** The volume of concrete and the weight of steel for the designed variations

|            | Volume of concrete [m <sup>3</sup> ] | Weight of steel [kg] |
|------------|--------------------------------------|----------------------|
| Variant 1  | 86,438                               | 4361,946             |
| Variant 2A | 67,411                               | 4759,971             |
| Variant 2B | 86,438                               | 4111,496             |

In the assessment, emissions of following substances are considered: carbon dioxide CO<sub>2</sub>, sulfur dioxide SO<sub>2</sub>, nitrogen oxides NO<sub>x</sub>, carbon monoxide CO, methane CH<sub>4</sub>, non-methane volatile organic compound NMVOC, nitrous oxide N<sub>2</sub>O, hydrochloric acid HCl, hydrofluoric acid HF, hydrogen sulphide H<sub>2</sub>S, ammonia NH<sub>3</sub>.

The effect of specific substance on each impact category was determined with using so-called characterization models. Characterization model for a specific impact category is a set of values that reflect the ability of various substances to damage the environment within this impact category. All of issued substances are converted to the equivalent amount of a reference substance by using these values (characterization factors). For this assessment, the characterization model recommended in Product category rules (PCR) for concrete products was used. [1]

Values of impact categories for 1 kg of each compound (cement, aggregate, plasticizer...) was then converted to the content in 1 m<sup>3</sup> of concrete. Finally, the values of impact categories for a real amount of concrete and steel were calculated for all variants. Impacts associated with the manufacturing of concrete were included in the evaluation, too. Furthermore, the values of environmental impacts associated with transportation of materials to the construction site was calculated.

### 3. Durability assessment

Consequently, the durability was determined for parking house variants. The results were applied for adjustment of the structural design to reach conformable service life of parking house variants.

According to current codes, the durability is not quantified, i.e. the lifetime is not determined. The durability is provided by simple prescriptions and recommendations ("deemed-to-satisfy" approach). There are many numerical models for calculation of remaining lifetime. For the durability of the structure, the time at which the steel reinforcement is depassivated due to carbonation is crucial. It's the moment when the carbonated layer reaches the reinforcement bars. The models characterize the dependence of the carbonation depth on time. The carbonation depth is influenced by many parameters which shall be covered by the model; they are the properties of concrete and the effects of the environment, in particular, the humidity and the carbon dioxide content in the air. The Papadakis et al. model [2] is considered the most comprehensive; it includes more detailed data on the composition of the concrete and the carbon dioxide concentration.

$$A = \sqrt{\frac{2[CO_2] \cdot D_{e,CO_2}}{[CH] + 3[CSH]}} \quad (1)$$

where  $D_{CO_2}$  is the effective diffusion coefficient of CO<sub>2</sub> in concrete (m<sup>2</sup>/s), [CO<sub>2</sub>] is the concentration of CO<sub>2</sub> in the environment (mol/m<sup>3</sup>), [CH] is the molar concentration of Ca(OH)<sub>2</sub> and [CSH] is the molar concentration of Calcium-Silicate-Hydrate.

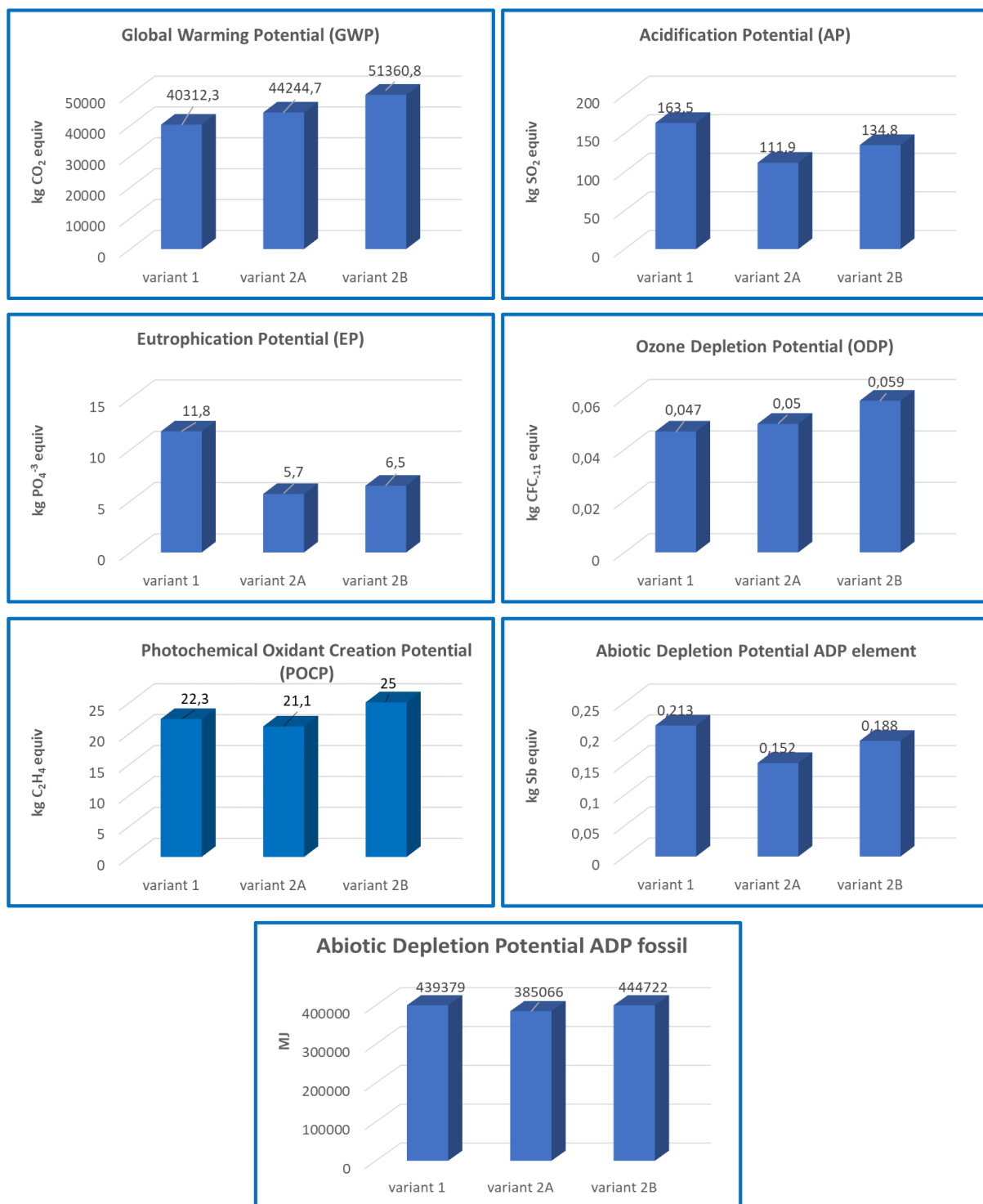
The durability of parking house was evaluated using a simplified version of Papadakis model, which is based on the contents of components in the concrete mixture and the humidity of the environment:

$$A = 350 \cdot \frac{\rho_c}{\rho_v} \cdot \frac{(w - 0,3)}{(1 + w \cdot \frac{\rho_c}{\rho_v})} \cdot f_{RH} \cdot \sqrt{\left(1 + \frac{\rho_c}{\rho_v} \cdot w + \frac{\rho_c}{\rho_a} \cdot \frac{m_a}{m_c}\right) \cdot c_{CO_2}} \quad (2)$$

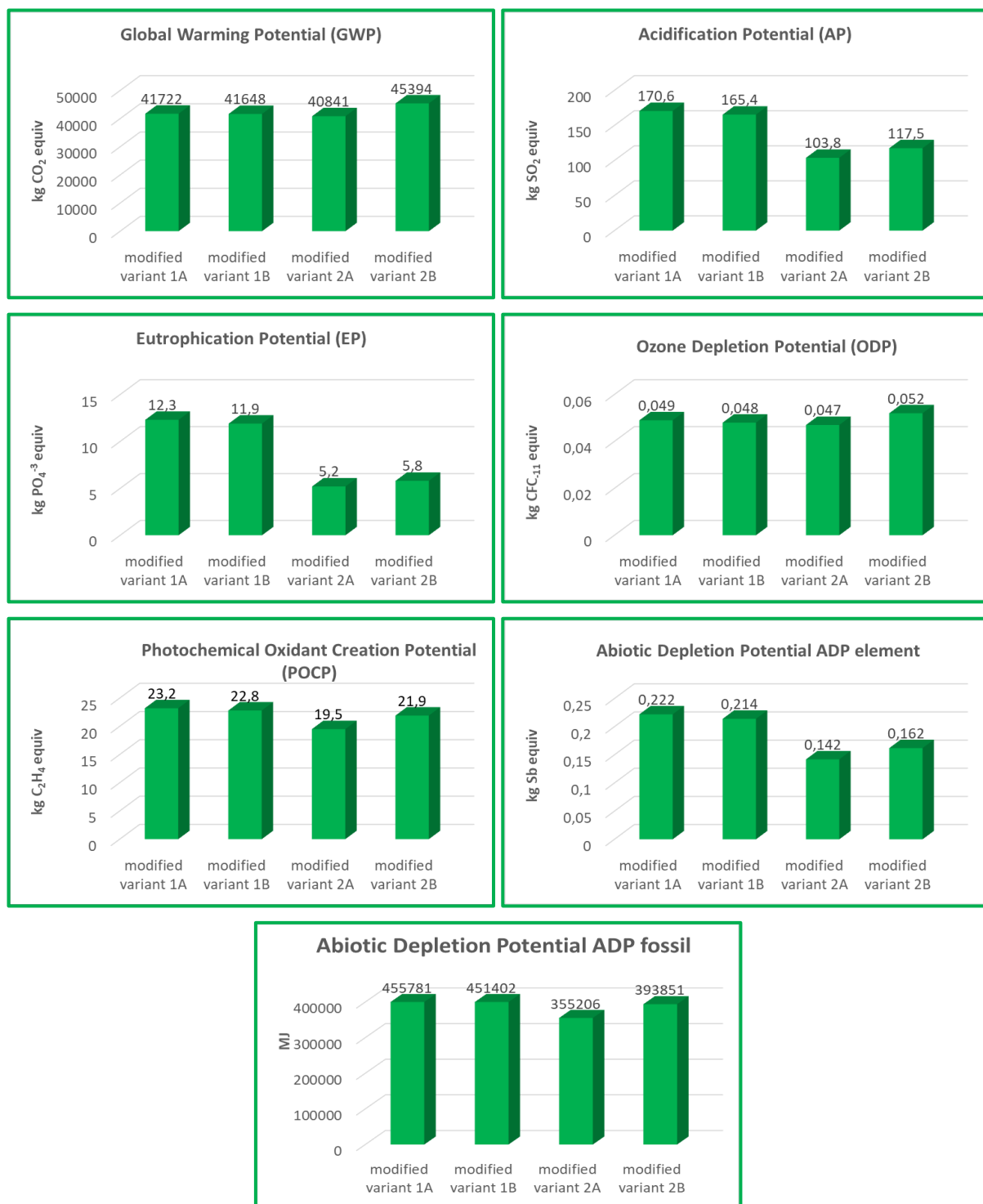
where  $\rho_c$ ,  $\rho_a$  and  $\rho_v$  are bulk densities of cement ( $\rho_c$ ), aggregates ( $\rho_a$ ) and water ( $\rho_v$ ) in kg/m<sup>3</sup>,  $m_a$  and  $m_c$  are weights of aggregate ( $m_a$ ), and water ( $m_c$ ) in kg,  $w$  is the water-cement ratio,  $c_{CO_2}$  is carbon dioxide concentration in air (mol/m<sup>3</sup>) and  $f_{RH}$  is a parameter dependent on the relative humidity of environment according to the following table:

**Table 3.** Values of the  $f_{RH}$  parameter:

| Relative humidity RH [%]        | 0 | 7 | 50    | 93  | 100 |
|---------------------------------|---|---|-------|-----|-----|
| Value of parameter $f_{RH}$ [-] | 0 | 0 | 0,425 | 0,5 | 0   |



**Figure 1.** Results of the life-cycle analysis of variants of the parking house floor structure



**Figure 2.** Results of the life-cycle analysis of variants of the parking house floor structure adjusted for targeted service-life

Initially, the initiation time was calculated. It is time, when the carbonated zone reached the level of the reinforcing steel or when the chloride concentration on level of the reinforcing steel reached the threshold value. After reaching this point, the reinforcing steel begins to corrode. The residual service life was calculated as the time during which the reinforcement area decreases so that it is no longer able to resist load effects.

Calculated values of service life are listed in table 4.

Parking houses are commonly designed for service life 50 years. The originally designed variant 1 (normal strength concrete) did not reach the required value, therefore the design was modified. The durability was increased in two alternatives: in the first case the reinforcement cover was increased (1A), in the second case the amount of reinforcement was increased (1B). On the other hand, the calculated life-cycle of the variants from high performance concrete was unreasonably long. Accordingly the structures 2A and 2B were modified to decrease the long life-cycle by reduction of the cover layer, what decreased the material consumption.

**Table 4.** Calculated durability

| Service life of original variants<br>(years) |       | Service life of modified variants<br>(years) |      |
|----------------------------------------------|-------|----------------------------------------------|------|
| Variant 1                                    | 46,8  | Variant 1A                                   | 56,5 |
|                                              |       | Variant 1B                                   | 57,8 |
| Variant 2A                                   | 380,6 | Variant 2A                                   | 50,7 |
| Variant 2B                                   | 380,4 | Variant 2B                                   | 51,3 |

Based on the results of analysis, the originally designed variants were adjusted to reach the end of service life approximately 50 years, not lower. For high performance concrete variants, the thickness of the reinforcement cover was reduced. After that, the sustainability assessment was carried out again.

The modified variants were again assessed by LCA. Results of LCA are depicted below.

The results show that the lower is cement consumption, the lower is the environmental impact of the structure. For most categories the lowest environmental impacts results were reached for the variant which is designed from high performance concrete (HPC) and the mechanical properties are used to reduce the thickness of the slab. Although environmental impacts of the unit amount of high-performance concrete are due to cement and plasticizer content higher than unit amount of normal-strength concrete, the total environmental impacts of the structure from high performance concrete are usually smaller thanks to significant material savings.

It is also interesting to compare original variants and variants designed to comply with target life-cycle. The durability analysis and determination of lifetime of the structure has shown that standards requirements can lead to a solution that is both uneconomical and unsustainable. Modern materials can provide durability and sufficient protection of reinforcement for lower cover than cover layer required by code prescriptions. Application of advanced cement composites is recommended especially for structures exposed to aggressive environment.

Unfortunately for common designing, the durability assessment of structures is quite challenging. Determination of the input values for the durability analysis is problematic. The environmental parameters are uncertain, and they may change over time. There is a large number of mathematical models for calculation of durability, but the service life significantly differs depending on used mathematical model or calculation method. The results should be compared and with common rates of degradation processes known from experience and the most reliable method for analysis should be chosen.

#### 4. Conclusions

The study showed that the application of durability assessment and service life determination that allow the structural design to be adjusted accordingly, leads to a reduction in environmental impacts and a better use of the potential of modern outstanding materials.

The design according to deemed to satisfy set of rules, for common concretes leads to the proposal of structures which do not reach the required life cycle values in a more precise analysis. On the other hand, the life cycle determined by simplified methods for new cement composites is economically overdesigned.

In the LCA analysis of cement-based materials, cement consumption is the decisive factor for almost all categories in concern.

LCA is used to compare and find a more appropriate solution with respect environmental impacts. It usually means finding of the better material solution. However, for the sustainable design, the correct structural design, detailing and full utilization of outstanding material properties of modern cement composites is often more important. Recent progress in science and research has brought modern materials and advanced technologies. Their potential can be fully exploited if corresponding advanced computing tools and suitable models are used for the design of structure with optimal service life and structural system and the potential of the material is efficiently exploited.

The benefit and great value of the presented approach is linking the design of reinforced concrete structures and their LCA analysis with durability assessment and life cycle evaluation.

#### Acknowledgments

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