

# Sustainability and durability analysis of reinforced concrete structures

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**Abstract.** The article describes an assessment of reinforced concrete structures in terms of durability and sustainable development. There is a short summary of findings from the literature on evaluation methods for environmental impacts and also about corrosive influences acting on the reinforced concrete structure, about factors influencing the durability of these structures and mathematical models describing the corrosion impacts. Variant design of reinforced concrete structure and assessment of these variants in terms of durability and sustainability was performed. The analysed structure was a concrete ceiling structure of a parking house for cars. The variants differ in strength class of concrete and thickness of concrete slab. It was found that in terms of durability and sustainable development it is significantly preferable to use higher class of concrete. There are significant differences in results of concrete structures durability for different mathematical models of corrosive influences.

## 1. Introduction

In past years, the issue of sustainable development and the impact of construction activities on the environment were often discussed. Compared with other sectors, these impacts are rather significant, especially in terms of consumption of material resources and in terms of greenhouse gas production. It is desirable to minimize these environmental impacts by suitable design and material selection. The problematics of the environmental impact is closely related to the service life of buildings. Buildings with high durability required fewer repairs during the course of their existence. Furthermore, it takes a longer time before they reach the state when their demolition and construction of a new building is needed. Environmental impacts associated with construction are then compensated by longer building operation without the necessary repairs. In this work variants of the design in terms of sustainable development and durability were compared.

## 2. Methods

### 2.1. A description of the structure

The analysis was performed for a simple construction — a concrete ceiling structure of a garage parking house for cars. The variants differ in strength class of concrete and thickness of concrete slab. One of the variants was designed from normal strength concrete (C35/45), the other variants were designed 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. In the other case these benefits were used to reduce the volume amount of steel. The parameters of the variants and the concrete recipes are shown in the following tables:

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

<b>The parameters of the variants</b>			
<b>Variant</b>	<b>1</b>	<b>2A</b>	<b>2B</b>
Strength class of concrete	C35/45	C90/105	C90/105
Spacing of rebars [mm]	120	100	130
Rebar diameter [mm]	8	8	8
$A_{s,req}$ [mm <sup>2</sup> ]	408,0263	486,7253	384,4082
$A_{s,prov}$ [mm <sup>2</sup> ]	418,879	502,6548	386,6576
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

**Table 2.** Recipe of concrete C35/45-XC4, XD3-C1 0,2-D<sub>max</sub>16-S4.

Cement 42,5 R	335 kg/m <sup>3</sup>
Water	135 kg/m <sup>3</sup>
Coarse aggregate (8-16 mm)	780 kg/m <sup>3</sup>
Medium aggregate (4-8 mm)	290 kg/m <sup>3</sup>
Fine aggregate (0-4 mm)	750 kg/m <sup>3</sup>
Limestone	110 kg/m <sup>3</sup>
Plasticizing admixture	3,7 kg/m <sup>3</sup>
Silica fume	14 kg/m <sup>3</sup>

**Table 3.** Recipe of concrete C90/105-XC4, XD3-C1 0,2-D<sub>max</sub>16-S4.

Cement 52,5 R	500 kg/m <sup>3</sup>
Water	165 kg/m <sup>3</sup>
Coarse aggregate (8-16 mm)	700 kg/m <sup>3</sup>
Medium aggregate (4-8 mm)	220 kg/m <sup>3</sup>
Fine aggregate (0-4 mm)	860 kg/m <sup>3</sup>
Plasticizing admixture	4,5 kg/m <sup>3</sup>

Reinforcement is from steel B500B. The design variants were assessed in terms of ultimate limit state and in terms of service limit state, too.

## 2.2. Sustainability assessment

Evaluation in terms of sustainable development was based on 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 whole life-cycle or at least on its significant part. So, 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 called 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 4.** The volume of concrete and the weight of steel for the designed variations.

	Volume of concrete [m <sup>3</sup> ]	Weight of steel [kg]
Variant1	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. In this assessment, for the transport of concrete the nearest concrete mixing plant was considered – it was the concrete

mixing plant in Benešov (the distance from the construction site is 10,6 km). Also for the steel reinforcement the nearest reinforcement manufactory was considered – the reinforcement manufactory in Prague (the distance from the construction site is 36,7 km). Finally, the values of environmental impacts associated with the transfer of these materials during the realization of the building (lifting and transport by a crane) was calculated.

### 2.3. Durability assessment

Building durability assessment method is not normatively determined yet, therefore the assessment was based on selected mathematical models, which describe the progress of the degradation phenomena in time. There are many different mathematical models for particular degradation phenomena, but for other degradation phenomena precise mathematical relationships were not formulated yet. The assessment included an effect of carbonation and an effect of chloride attack.

There are plenty of mathematical models for the time dependence of carbonation depth, because this degradation phenomenon is considered the most important within the framework of reinforced concrete structures. For durability of the construction the time when the steel reinforcement is depassivated due to carbonation (the time when carbonated layer reaches the level of reinforcement bars) is important. This time is in the literature referred to as the initiation time. The physical principle of carbonation mathematical models is diffusion, so they are based on II. Fick's law, which is described by the differential equation:

$$\frac{\partial c}{\partial t} = D \cdot \frac{\partial c^2}{\partial x^2} \quad (1)$$

where  $c$  is concentration,  $t$  is time and  $x$  is the distance, in this case, the distance from the surface. The thickness of carbonated layer can be determined from the relation:

$$x_c = A \cdot \sqrt{t}$$

where  $x_c$  is the thickness of carbonated layer (mm),  $t$  is the elapsed time (years) and the  $A$  is a coefficient, which is calculated according to the used model. The coefficient  $A$  is different for different mathematical models. All models for the calculation of coefficient  $A$  include a parameter dependent on a type of used concrete. Most often, it is the value of water-cement ratio and compressive strength. Some models dependent on the weight of the components of concrete mixture (cement, aggregate, water) and their bulk densities. Sometimes also the type of used cement is taken into account. The coefficient  $A$  also sometimes depends on environmental effects, such as humidity or carbon dioxide content in air.

Model, which is currently considered the most comprehensive, includes detailed information about the composition of the concrete mixture and depends also on the concentration of carbon dioxide in air. The model dates back to 1992 and its author is V. G. Papadakis et al. [6]

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

where  $D_{CO_2}$  is the effective diffusion coefficient of  $CO_2$  in concrete ( $m^2/s$ ),  $[CO_2]$  is the concentration of  $CO_2$  in the environment ( $mol/m^3$ ),  $[CH]$  is the molar concentration of  $Ca(OH)_2$  and  $[CSH]$  is the molar concentration of Calcium-Silicate-Hydrate.

The model is valid for the concrete, where a substantial part of hydration process is completed and whose diffusion coefficient has a constant value. So, the structure should be in a relatively constant environment. However, the model for fluctuating environmental conditions has not been created yet. If the environmental conditions are unstable, the results must be evaluated with caution.

The calculation of the diffusion coefficient is quite difficult and requires detailed information about the material. However, it is possible to use a simplified version of this model, which is based on the contents of components in the concrete mixture and the humidity of the environment:

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

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

**Table 5.** The 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

It is possible to use an effective value of water-cement ratio  $w_{\text{eff}}$  for models dependent on water-cement ratio. It is a modified value of water-cement ratio reflecting the influence of supplementary cementing materials (SCM) on the behavior of the material. [5]

$$w_{\text{eff}} = m_v / (m_c + k \cdot \text{SCM}) \quad (4)$$

where  $m_v$  and  $m_c$  are weights of cement and water,  $k$  is a parameter depending on the type of supplementary cementing material (fly ash, silica fume, slag) and  $\text{SCM}$  is the total amount of the SCM. The models are very often based on the value of water-cement ratio. The water-cement ratio has a direct effect on the porosity of the material and therefore also on its durability. However, there are not always taken into account other factors affecting the rate of carbonation. The advantage of these models is simplicity of the calculation and low requirements for input data. An example is De Sitter's model from 1985 [7]:

$$A = \sqrt{\frac{46w - 17,6}{2,7} \cdot R \cdot k} \quad (5)$$

where  $w$  is the water-cement ratio,  $R$  is the coefficient depending on the type of cement and  $k$  is the coefficient reflecting the ambient humidity. Similar is Kishitani's model from 2005 [3]:

$$\text{For } w < 0,6: A = R_1 \cdot \sqrt{0,639 w - 0,244} \quad (6)$$

$$\text{For } w \geq 0,6: A = R_2 \cdot \sqrt{\frac{(w - 0,25)^2}{0,345 + w}} \quad (7)$$

where  $R_1$  and  $R_2$  are coefficients depending on a type of cement.

A lot of models are dependent on a compressive strength. An example is Bob's model from 1990 [6]:

$$A = \frac{150 \cdot C \cdot k \cdot d}{f_c} \quad (8)$$

where  $f_c$  is the compressive strength (MPa),  $C$  is a coefficient depending on the type of cement, the  $k$  is coefficient reflecting the humidity conditions of the environment, and  $d$  is a coefficient depending on the content of  $\text{CO}_2$  in the environment.

Duval's model from 1992 [4] is also dependent on the compressive strength:

$$A = \sqrt{365} \cdot \left( \frac{1}{2,1 \cdot \sqrt{f_c}} - 0,06 \right) \quad (9)$$

where  $f_c$  is the compressive strength (MPa).  
Similar is Parrot's model from 1987 [4]:

$$A = \sqrt{251} \cdot \exp(-0,05 \cdot f_c) \quad (10)$$

where  $f_c$  is the compressive strength (MPa).

For the final calculation of durability a carbonation model formulated by Papadakis in year 1992 was chosen. For comparison, the service life was also calculated using the Bob's model from year 1990. Mathematical model which was used for the chloride attack depends on concrete chloride diffusion coefficient and on surface chloride concentration in concrete. It dates back to 1972 [7].

$$c(x,t) = c_{s,0} \left[ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{t \cdot D_{e,Cl}}} \right) \right] \quad (11)$$

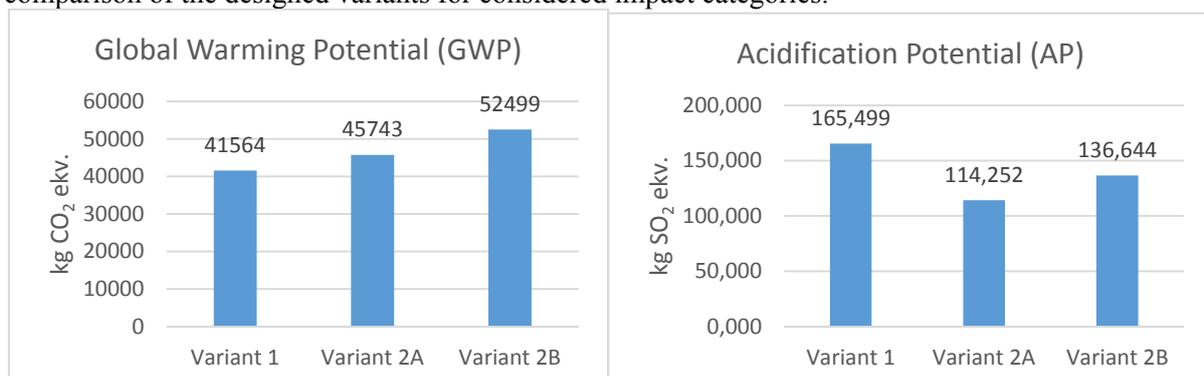
where  $c(x,t)$  is the chloride ion concentration,  $D_{e,Cl}$  is the effective diffusion coefficient for chlorides ( $\text{mm}^2/\text{year}$ ),  $c_{s,0}$  is the concentration of chlorides on the surface of structure,  $x$  is the distance from the surface of structure (mm) and  $t$  is the exposure time (years).  $\operatorname{erf}$  is the error function.

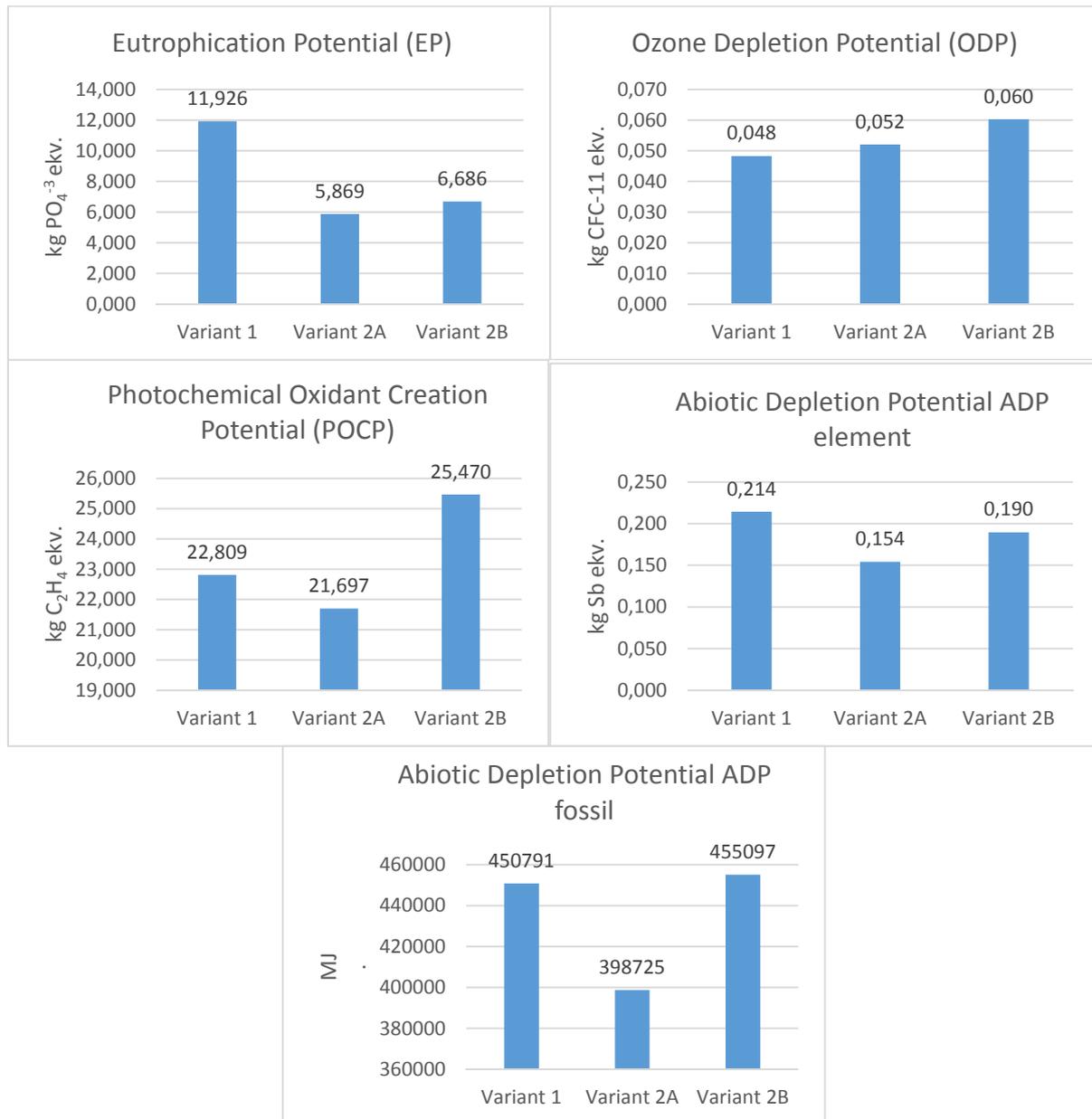
At first, the initiation time was calculated. It is time, when the carbonated zone reached the level of the reinforcing steel or when the chloride concentration on level of the reinforcing steel reached the threshold value. After reaching this point, the reinforcing steel begins to corrode. The residual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

### 3. Results

#### 3.1. Sustainability assessment

The results of the sustainability assessment depend on the specific environmental impact. For most impacts the best 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. The variant in which the outstanding HPC properties are used to reduce the amount of steel is not so advantageous, according to this evaluation. In the assessment of effect on the global warming the most favourable results were calculated for the variant designed from normal-strength concrete. The same result was obtained also for the assessment of an effect on the stratospheric ozone depletion. The reason is evidently the usage of a higher volume of cement and plasticizer. The following figure shows the comparison of the designed variants for considered impact categories.

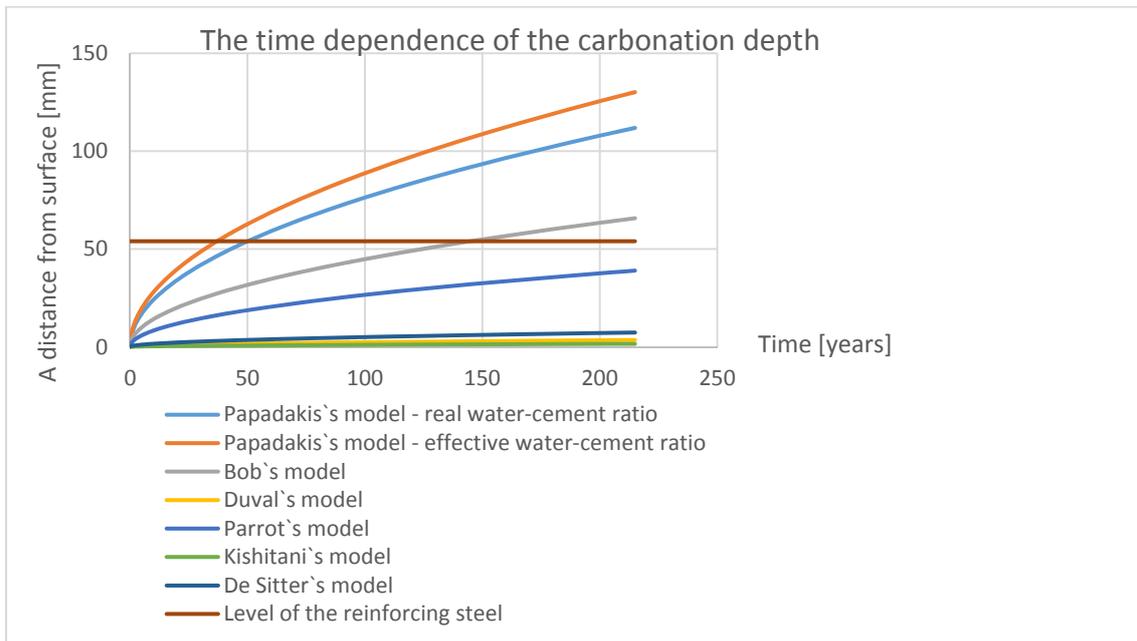




**Figure 1.** Comparison of the designed variants regarding sustainability.

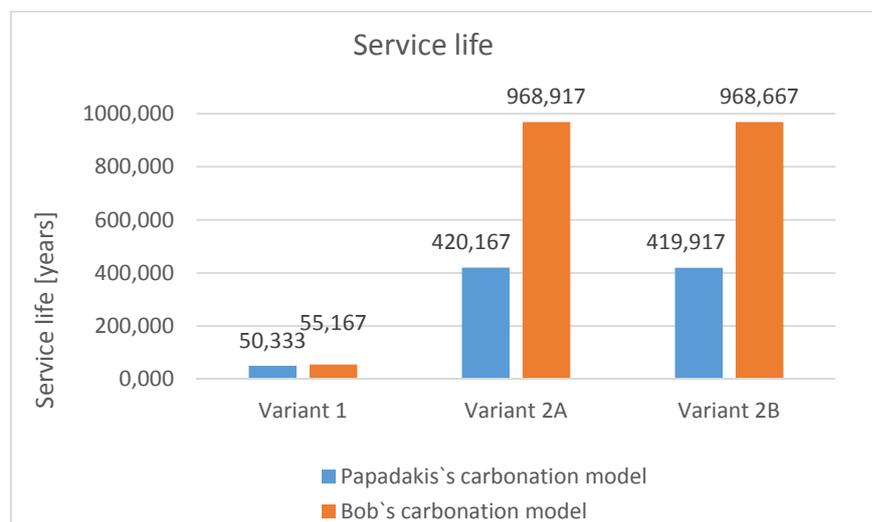
### 3.2. Durability assessment

At first, several different mathematical carbonation models were exploited for durability assessment of the variant 1. The results differed significantly, depending on the model. The most favourable results were obtained for models which depend on a smaller number of parameters, for example, only on a compressive strength or water-cement ratio. The results obtained using multicriterial models (for example the Papadakis’s model) were not so favourable, although they correspond with velocities of carbonation referred in literature. The following figure shows the time dependence of the carbonation depth for different mathematical models.



**Figure 2.** The time dependence of the carbonation depth according to different mathematical models.

Regardless of used mathematical models, the service life of variants from high performance concrete is significantly higher compared to the variant from normal concrete. When Bob's model of carbonation was used, the results are quite unrealistic, especially for variants 2A and 2B (variants from HPC). So, the service life calculated with using Papadakis's model was considered decisive. The following figure shows the service life of designed variants.



**Figure 3.** Service life of designed variants.

*3.3. A modification of the design*

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. For the variant 1, the durability was increased in two alternatives: in the first case the reinforcement cover was increased, in the second case the amount of reinforcement was increased. After that, the sustainability assessment was carried out again. For most impacts the results are better for variants from high performance concrete.

The best results were obtained for variant designed from high performance concrete with reduced thickness of the slab (variant 2A). The variant with reduced amount of steel (variant 2B) is not so advantageous, according to this analysis. For the normal-strength concrete variants, the variant, in which amount of reinforcement was increased according to durability demands, is more advantageous regarding environmental impacts.

#### 4. Discussion

Advantages of using high performance concrete are clearly obvious from this assessment. 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 was proven that the outstanding mechanical properties of high-performance concrete should be preferably utilised to reduce the thickness of the slab.

Also regarding durability the variants designed from high performance concrete are significantly advantageous. The evaluation concluded that in case of using these concretes it is possible to reduce the thickness of a cover layer much lower than values given by the standard. Especially for structures in aggressive environment very significant material savings can be achieved.

#### 5. Conclusion

To meet sustainable development principles, it is more advantageous to design the structures from the high performance concrete. However, it is always necessary to consider all of the aspects, for example the economic efficiency and requirements for the building (e.g. the requirements for the surfaces quality). In terms of durability, the variants designed from high performance concrete are also significantly profitable. Possible reduction the thickness of a reinforcement cover brings about material savings. It is significant especially in aggressive environment. If the thickness of a reinforcement cover is designed according to standard, the service life of a HPC structure is much longer than the required service life. However, it should be considered whether it is even advisable to use such a long life of buildings, particularly in relation to its moral life service and its purpose.

An accurate durability assessment of structures is very problematic. It is often impossible to determine exactly the input values for the analysis. It is typical primarily for parameters of environment, which, moreover, 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.

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