Variant design of concrete structure in relation to durability of the structure and environmental impacts

Anna Horáková, Alena Kohoutková and Iva Broukalová

Department of Concrete and Masonry Structures
Faculty of Civil Engineering, Czech Technical University in Prague
Thákurova 2077/7, 166 29 Praha 6 – Dejvice, Czech Republic

Abstract

The paper describes an assessment of reinforced concrete structures in terms of durability and environmental impacts. The article includes a short summary of the literature search on evaluation methods for environmental impacts, corrosive impacts on the reinforced concrete structure, and factors influencing the durability of concrete structures. An overview of mathematical models describing the corrosion of concrete is presented. Variant design of a floor structure in a car parking house was performed. The variants differ in type of a structure (prestressed concrete structure or reinforced concrete structure), strength class of concrete and thickness of concrete slab. All variants are assessed in terms of durability and sustainability. The paper presents results of life-cycle assessment of all variants, comparison of the variants and recommendations for practical designing.

1 Introduction

In past years, the issue of sustainable development and the impact of construction activities on the environment were often discussed. It is desirable to minimize the environmental impact by suitable design, optimal manufacturing process 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 [7]. 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 floor structure of a parking house for cars. The variants differ in type of a structure (prestressed concrete structure or reinforced concrete structure), strength class of concrete, thickness of concrete slab and amount of reinforcement. The prestressed concrete structures are designed as prefabricated structures made from precast elements. The slab is designed from prestressed precast panels and the beams are also prestressed. The columns are designed from reinforced concrete in all variants. The structural sketches are shown in the following picture.

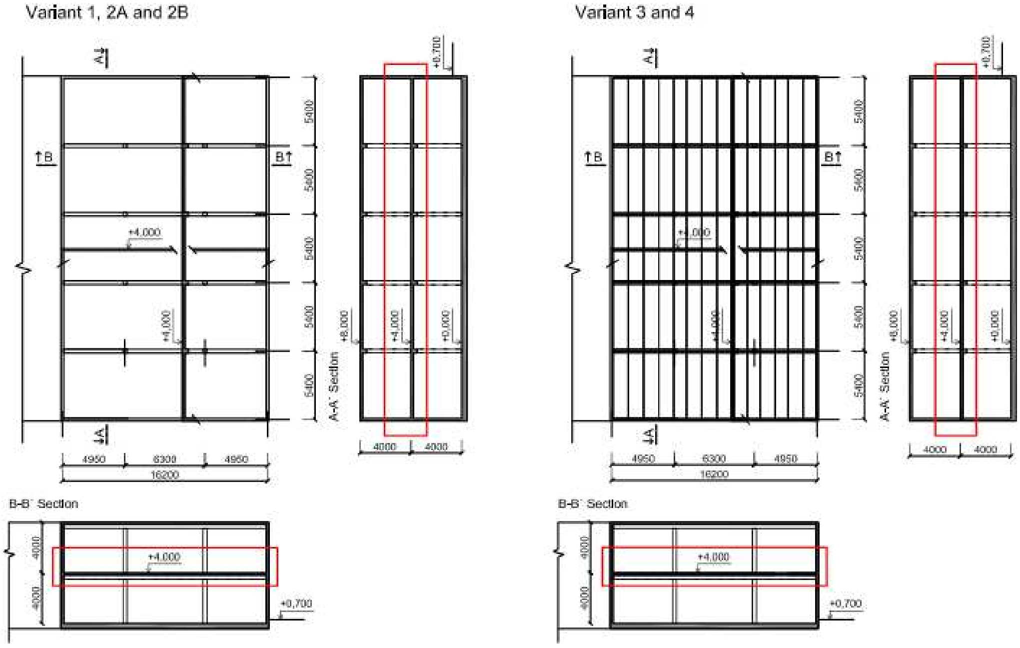

Fig. 1 The structural sketches.

Variants 1 and 3 were designed from normal strength concrete (C35/45), the other variants were designed from high performance concrete (C90/105). In the variant 2A the mechanical properties of high performance concrete were used to reduce the thickness of the slab. In the variant 2B these benefits were used to reduce the volume amount of steel. Variant 4 is the prestressed concrete structure designed from high performance concrete (C90/105). The parameters of the variants and the concrete recipes are shown in the following tables.

Table 1 Composition of concrete C35/45-XC4, XD3-Cl 0,2-Dmax16-S4.

Cement 42,5 R	335	kg/m^3
Water	135	kg/m^3
Coarse aggregate (8-16 mm)	780	kg/m^3
Medium aggregate (4-8 mm)	290	kg/m^3
Fine aggregate (0-4 mm)	750	kg/m^3
Limestone	110	kg/m^3
Plasticizing admixture	3.7	kg/m^3
Silica fume	14	kg/m^3

Table 2 Composition of concrete C90/105-XC4, XD3-Cl 0,2-D_{max}16-S4.

Cement 52,5 R	500	kg/m^3
Water	165	kg/m^3
Coarse aggregate (8-16 mm)	700	kg/m^3
Medium aggregate (4-8 mm)	220	kg/m^3
Fine aggregate (0-4 mm)	860	kg/m^3
Plasticizing admixture	4.5	kg/m^3

Table 3 The parameters of the variants.

The parameters of the variants					
Variant	1	2A	2B	3	4
Type of a structure	Reinforced concrete structure	Reinforced concrete structure	Reinforced concrete structure	Prestressed concrete structure	Prestressed concrete structure
Strength class of concrete	C35/45	C90/105	C90/105	C35/45	C90/107
Slab					
Spacing of rebars [mm]	120	100	130	-	-
Number of prestressing strands	-	-	-	8	8
Rebar diameter [mm]	8	8	8	15.5	15.5
$A_{s,prov}$ [mm^2]	628.3185	753.9822	579.9864	1120	1120
Type of reinforcement	B500B	B500B	B500B	Y1770S7-15,7	Y1770S7-15,7
Cover of reinforcement [mm]	50	45	45	50	45
Thickness of slab [mm]	180	140	180	130	110
Beams					
Dimensions of the beams [mm]	500 x 300	450 x 250	450 x 300	500 x 300	400 x 300
$A_{s,prov}$ [mm^2]	942.5	1005.3	1005.3	840	840

The design variants were assessed in terms of ultimate limit state and in terms of service limit state, too.

2.2 Assessment in terms of environmental impacts

Evaluation in terms of sustainable development was performed using Life-cycle assessment (LCA) according to relevant standards [1]. LCA is a method of evaluation the environmental impact of a product, which usually considers the whole life-cycle or at least its significant part. So, the assessment includes obtaining of raw materials, their transport to the place of processing, manufacturing of a final product, use of the product and maintenance or repairs if necessary, and final disposal of the product. In some cases, the prediction of the course of the phase of use is not possible and the evaluation includes only the chosen part of life cycle. 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. 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, manufacturing of precast elements (panels, beams and columns), transport of these materials and elements to the site of the building and the building realization. The following table shows the volume of concrete and the weight of reinforcing and prestressing steel for the designed variants.

Table 4 The volume of concrete and the weight of steel for the designed variants.

	Volume of concrete [m^3]	Weight of reinforcing steel [kg]	Weight of prestressing steel [kg]
V1	87.4728	4461.381168	0
V2A	68.033	4860.826671	0
V2B	86.5368	4212.351671	0
V3	67.6604	316.742	4272.912
V4	57.0068	298.651	4272.912

Note: some reinforcing steel is used also in the variants with prestressed concrete structures. The columns are designed from reinforced concrete and the beams have steel shear reinforcement.

In the assessment, emissions of following substances are considered: carbon dioxide CO_2, sulfur dioxide SO_2, nitrogen oxides NO_x, carbon monoxide CO, methane CH_4, non-methane volatile organic compound NMVOC, nitrous oxide N_2O, hydrochloric acid HCl, hydrofluoric acid HF, hydrogen sulphide H_2S, ammonia NH_3.

The effect of specific substance on each impact category was determined using so-called characterization models. Characterization model for a specific impact category is a set of values, which reflect the ability of various substances to damage the environment within the impact category in consideration. All 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 component of concrete (cement, aggregate, plasticizer…) were then converted to the content in 1 m^3 of concrete. Finally, the values of impact categories for a real amount of concrete, reinforcing steel and prestressing steel were calculated for all variants. Impacts associated with the manufacturing of concrete and manufacturing of precast elements were included in the assessment too. Furthermore, the values of environmental impacts associated with transportation of materials to the construction site were calculated. Finally, the values of environmental impacts associated with the transfer of materials and precast elements during the realization of the building (lifting and transport by a crane) were calculated [8].

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. 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 [4]. 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. The thickness of carbonated layer can be determined from the relation:

$$\mathrm{xc} = \mathrm{A}.\sqrt{t} \tag{1}$$

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 depende on the weight of the components of concrete mixture (cement, aggregate, water) and their bulk densities. The coefficient A also depends on environmental effects in some models, 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]

$$A = \sqrt{\frac{2[CO_2].D_{e,co_2}}{[CH]+3[CSH]}} \tag{2}$$

where D_{CO2} 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 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.

$$\mathrm{A} = 350.\frac{\rho_c}{\rho_v}\frac{(w-0{,}3)}{(1+w.\frac{\rho_c}{\rho_v})}.\,f_{RH}.\sqrt{(1+\frac{\rho_c}{\rho_v}.w+\frac{\rho_c}{\rho_a}.\frac{m_a}{m_c}).c_{CO_2}} \tag{3}$$

where ρc, ρa and ρv are bulk densities of cement, aggregates and water (kg/m3), ma and mc are weights of aggregate, and water (kg), w is the water-cement ratio, c_{CO_2} is carbon dioxide concentration in air (mol/m3) and fRH is a parameter dependent on the relative humidity of environment. It is possible to use an effective value of water-cement ratio weff 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.

The models are very often based on the value of water-cement ratio. An example is Kishitani`s model from 2005 [3].

$$\text{For } w < 0{,}6\text{: } A = R1.\ \sqrt{0{,}639\,w\ -\ 0{,}244} \tag{4}$$

$$\text{For } w \geq 0{,}6\text{: } A = R2.\ \sqrt{\frac{(w-0{,}25)^2}{0{,}345+w}} \tag{5}$$

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

A lot of models are dependent on a compressive strength [2], [5]. An example is Bob`s model from 1990 [5].

$$A = \frac{150\,.\,C\,.\,k\,.\,d}{f_c} \tag{6}$$

where fc 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 CO_2 in the environment.

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 [6].

$$c(x,t) = c_{s,0}\left[1 - erf\left(\frac{x}{2\sqrt{t\,.\,D_{e,Cl}}}\right)\right] \tag{7}$$

where $c(x,t)$ is the chloride ion concentration, $D_{e,Cl}$ is the effective diffusion coefficient for chlorides (mm^2/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). *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 Assessment in terms of environmental impacts

The results of the sustainability assessment are related to the specific environmental impact. For acidification and eutrophication of the environment, the best results were reached for the variant which is designed as a reinforced concrete structure 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 variants designed from normal-strength concrete (variants 1 and 3). The same result was obtained also for the assessment of an effect on the photochemical oxidant creation potential. The reason is evidently the usage of a higher volume of cement and plasticizer. Variants designed as prestressed concrete structures seem to be favorable in the assessment of an effect on the abiotic depletion potential - element. The reason is obviously in a lower volume of concrete used for these variants. On the contrary, in the assessment of an effect on the abiotic depletion potential – fossil results for these variants were not so favourable. Probably, it is caused by high energy consumption during the production of the precast elements. The following figure shows the comparison of the designed variants for considered impact categories.

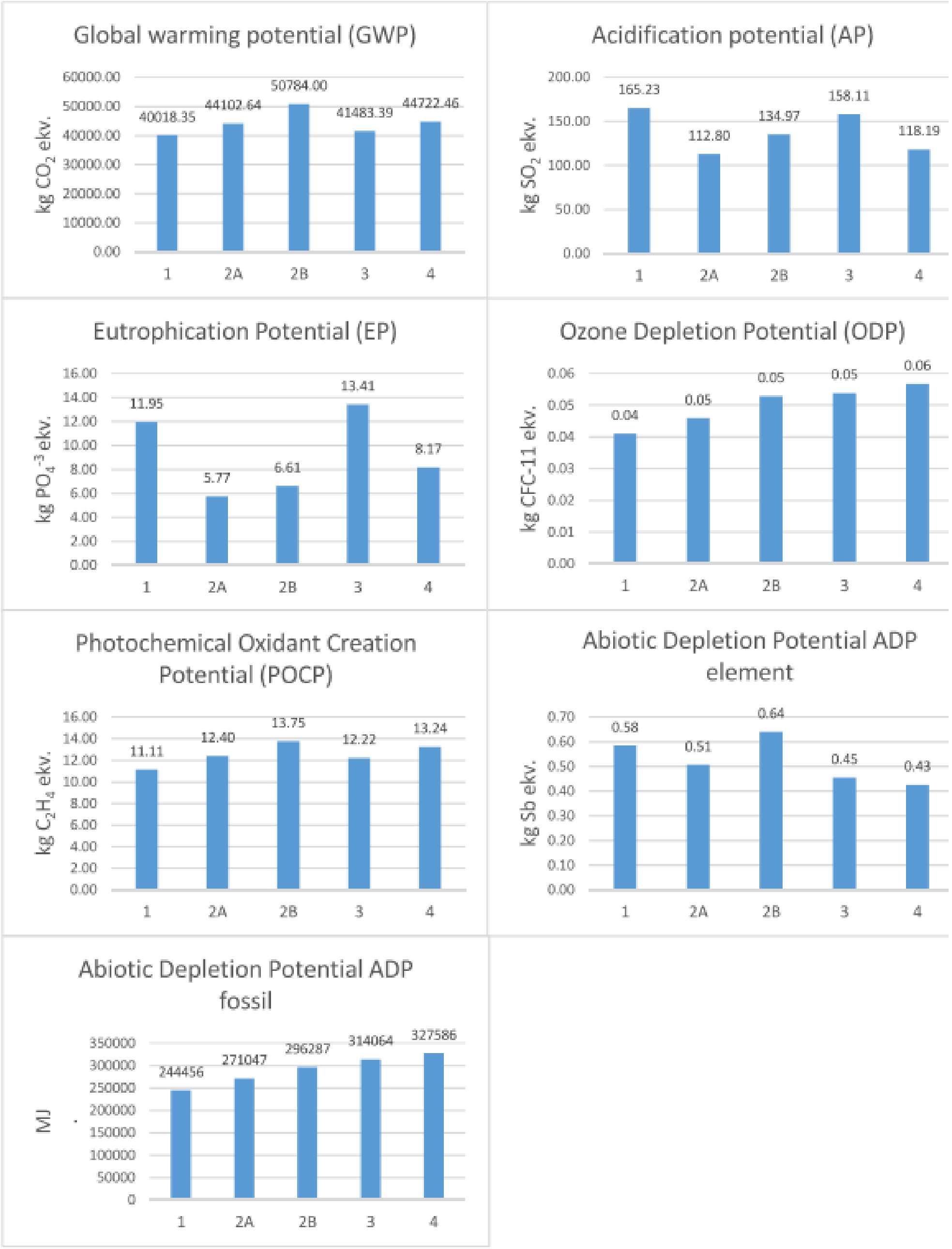

Fig. 2 Comparison of the designed variants regarding sustainability.

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.

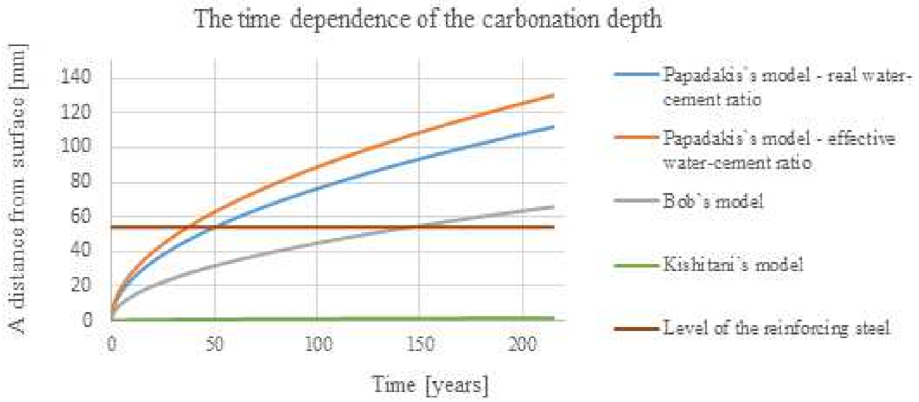

Fig. 3 The time dependence of the carbonation depth according to mathematical models.

Regardless of used mathematical models, the service life of variants from high performance concrete is significantly higher compared to the variant from normal concrete. Reinforced concrete structures (variants 1, 2A and 2B) were designed to prevent cracks in the concrete. So, the results are similar for these structures and for prestressed concrete structures and depend only on the strenght class of concrete. Common reinforced concrete structures crack, the service life of these structures will be lower compared to structure without cracks. So, in this case the service life of variants designed as presressed concrete structures would be higher compared to variants designed as reinforced concrete structure. Unfortunately there are only few mathematical models for concrete structures with cracks. When Bob`s model of carbonation was used, the results are quite unrealistic, especially for 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.

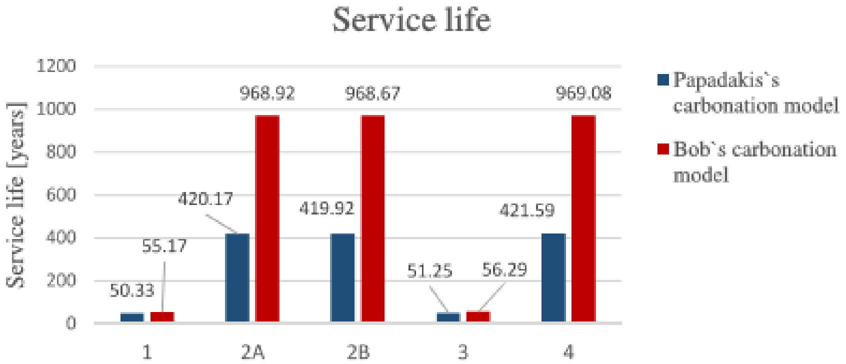

Fig. 4 The time dependence of the carbonation depth according to mathematical models.

4 Discussion

Advantages of using high performance concrete and designing prestressed structure 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. By usig prestress it is also possible to reduce the thickness of the concrete slab. It is very significant especially for the assessment of an effect on the abiotic depletion potential – element. The disadvantage is the high cost of this technology.

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.

5 Conclusion

To meet sustainable development principles, it is most advantageous to design the concrete structures as prestressed concrete 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 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 commonrates of degradation processes known from experience and the most reliable method for analysis should be chosen.

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