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# Optimization of RC Structures with Regard to Amount of Embodied CO<sub>2</sub> Emissions

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**Abstract.** The volume of CO<sub>2</sub> emissions (and other greenhouse gases) has been rising almost continuously for several decades. Concrete is the most used man-made material in the world, thus the construction of reinforced concrete (RC) structures is associated with high environmental impact, mainly due to the consumption of cement as binder for concrete and steel as reinforcement. This article analyses the available options for the design of RC structure to reduce embodied CO<sub>2</sub> emissions. The main part of the article is a case study demonstrating optimization of the load-bearing structure of multi-storey building. Emphasis was placed on achieving the optimal variant in terms of CO<sub>2</sub> emissions, while maintaining a comparable cost of the construction. The results of this study show that in this particular case the use of concrete with a lower strength brings lower environmental impact than of concrete with higher strength. The reason is that the production of lower strength concrete allows the use of cements with a lower clinker content which is decisive for CO<sub>2</sub> emissions. However, the use of concrete with higher strength allows more subtle structural members with lower content of concrete and potentially with higher durability.

## 1. Introduction

In 2015, United Nations adopted a resolution: Transforming our world: the 2030 Agenda for Sustainable Development [1]. This Agenda is a plan of action for people, planet and prosperity and should stimulate action up to 2030 in areas of critical importance for humanity and the planet. There were specified 17 Sustainable Development Goals (SDGs) which are integrated and indivisible and balance three dimensions of sustainable development: economic, social and environmental. Reducing greenhouse gas emissions, especially CO<sub>2</sub>, represents one of the most important trend across all sectors.

Construction industry as a main stakeholder responsible for the use of material and energy resources has a key role in the implementation of Sustainable Development Goals actions in the process of design, development and operation of buildings, roads, bridges and other infrastructure creating urban built environment. Considering continuing increase of cement production and its use, concrete and concrete structures play in this process significant role [2].

This article focuses on the possibilities of reducing CO<sub>2</sub> emissions in the framework of construction of RC structures. There are several ways to achieve this goal [3]. Most of them focus on the production of cement – especially Portland clinker, which is a key factor in production of CO<sub>2</sub> emissions. Many research attempts to partly replace Portland clinker with other addition or to improve the production of cement. For example, a MIT scientists study reports that by modifying the chemical composition of cement it is possible to obtain a concrete with higher strength and to achieve cement savings and thus



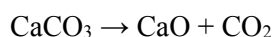
also lower CO<sub>2</sub> emissions [4]. Another example promising even greater results is an American invention of cement used to cure CO<sub>2</sub> instead of water. This binder, known as "solidia cement", absorbs CO<sub>2</sub> from the air and helps to reduce undesired emissions.

These or similar inventions have a great potential for reducing greenhouse gas emissions. But they must be confirmed by practical results, which is often the main stumbling block. They often require high financial cost that prevent mass expansion or they are economically unviable. This article is about reducing CO<sub>2</sub> emissions using only available technologies and materials on the market. This method is feasible in the design of any RC structure and does not require expensive investments or changes in the technology of concrete production.

## 2. Environmental impacts of cement production

As mentioned before, most of the research aimed at reducing CO<sub>2</sub> emissions in concrete is primarily concerned with cement. Its production is an energy-intensive process consisting of several phases. These include the quarrying raw materials, their transportation, crushing, grinding, homogenization, clinker burning, cement grinding, packing and transport to the customer. Thanks to modern technology, this process is much more environmentally friendly than before and cement plants invest a lot of money into environmental protection. For example, the use of alternative fuels instead of fossil fuels, the installation of new filter technologies to reduce pollutants. The other approach is optimization of cement composition in order to reduce clinker content.

From an environmental point of view, clinker burning is the most problematic phase of cement production. Most CO<sub>2</sub> emissions are released during calcination (thermal decomposition of limestone) according to the equation:



The residual emissions then arise from the combustion of fossil or alternative fuels. Each tonne of Portland clinker produced is associated with approximately 800-900 kg of CO<sub>2</sub> released into the air [6]. But the most cement plants nowadays mainly use alternative fuels that are cheap and their combustion results in less CO<sub>2</sub> emissions. Nevertheless, current data show that the cement industry is responsible for approximately 5-7 % of global greenhouse gas emissions [5,6]. This negative phenomenon has recently tried to suppress the cement industry by offering composite cements in which Portland clinker is partially replaced by some addition such as ground granulated blast furnace slag, ground limestone, fly ash, etc. Although in recent years the production of cement in the world continues to grow, CO<sub>2</sub> emissions are curbed also thanks to these composite cements [7].

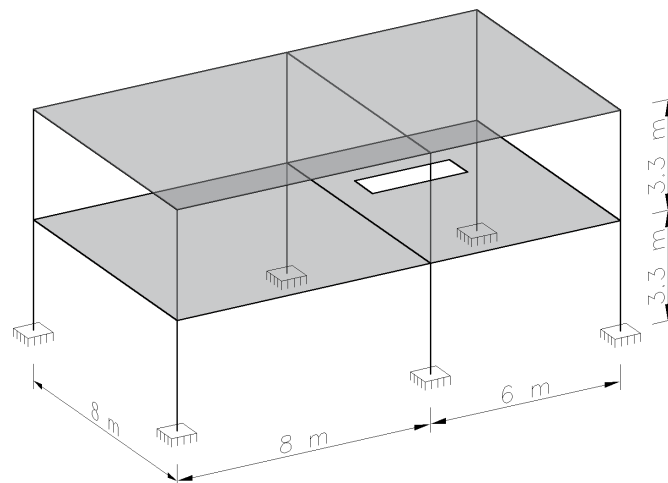
## 3. Case study

As already outlined in the introduction, the article discusses the possibilities of reducing CO<sub>2</sub> emissions by optimizing the load-bearing structure. The concrete strength class, the dimension of the structural elements (columns, walls, slabs, beams) and their reinforcement can be optimized with respect to the required parameters, which in this case are the CO<sub>2</sub> emissions and the financial expenses. Optimization was made for a better understanding in a case study in which the results were compared according to concrete strength classes.

The basic prerequisite for optimization is the existence of high-quality data that will be consistent with each other. The calculation includes the actual material cost (concrete, steel reinforcement), their transport to the construction site, the transfer of material on the site (concrete pumping, crane) and the use of formwork. The environmental data used for the calculation were taken from the research carried out at the Faculty of Civil Engineering CTU in Prague and correspond to the conditions of the Czech Republic [8]. Similarly, the national database of guide cost was used to estimation of construction cost [9].

### 3.1. Description of structure and its load

The case study was carried out on a small two-storey frame with two-span consisting of columns and locally supported RC slabs (Fig. 1). The dimensions of the structure are  $8 \times 14$  m in floor plan and 6.6 m in height. Columns are fixed to the pad foundation, but these are not included in optimization. On the first floor is omitted hole location of the stairs with dimensions of  $1 \times 3$  m. These basic dimensions are the same as for experimental frame OSEEB built at University Centre for energy Efficient Buildings [10].



**Figure 1.** Dimension of optimized construction

The structure was loaded with a permanent and an imposed load according to the European standards (Eurocodes). The permanent load, the first load case (LC1), included the self-weight of slab and the floor structure with an assumed load of  $2 \text{ kN/m}^2$ . Further, the slabs were loaded with an imposed load of  $3 \text{ kN/m}^2$  in three load cases – separately in the first field (LC2), separately in the second field (LC3) and both fields together (LC4). Other types of loading, such as wind and snow, were not considered for simplicity. Three load combinations were created for these load cases:

$$\text{CO1} = 1.35 \times \text{LC1} + 1.5 \times \text{LC2}$$

$$\text{CO2} = 1.35 \times \text{LC1} + 1.5 \times \text{LC3}$$

$$\text{CO3} = 1.35 \times \text{LC1} + 1.5 \times \text{LC4}$$

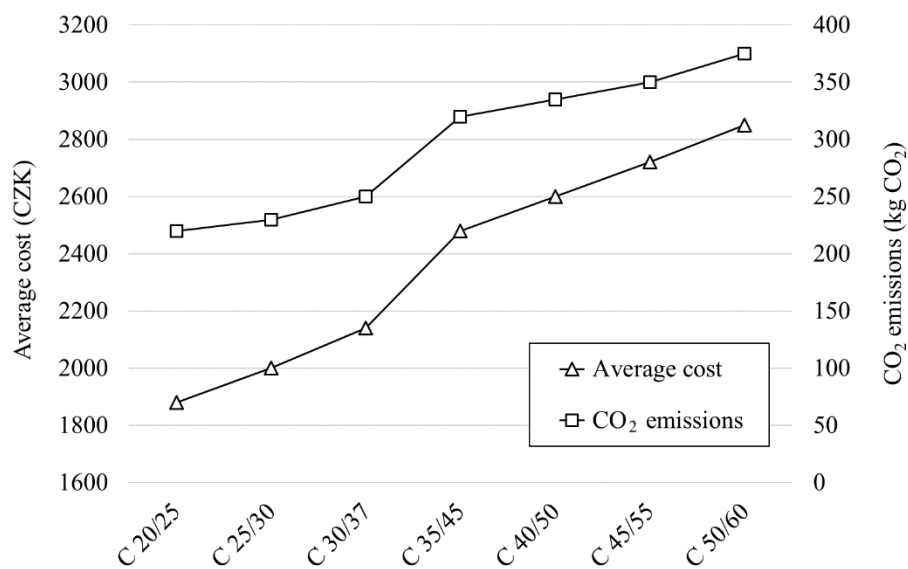
Finally, from these three combinations (CO1, CO2, CO3), a result combination was created. This result combination contains positive and negative extreme values that served to dimension the reinforcement.

### 3.2. Optimization

The load-bearing structure can be designed in many variants. It is dependent on the concrete strength class, based on this are determined dimensions of particular structural elements. But even within one strength class, it is possible to design elements of different cross-sections or thicknesses, which will subsequently require more or less reinforcement. For example, a square column with dimensions  $400 \times 400 \text{ mm}$  will be certainly less reinforced than a column with dimensions  $300 \times 300 \text{ mm}$ . It is not easy to predict whether it is better to use concrete with lower or higher strength, cross section of smaller or larger dimensions and so on. An important role plays the cost of material, its transport, the use of formwork and, last but not least, the overall character of the construction. The two-storey building will certainly have different features than the seven-storey building.

In our case, the optimization was performed according to the following procedure. In the first step the construction was modelled in RFEM software from Dlubal company [11], which is used for

structural analysis and enables design of reinforcement for structural elements, as well. Furthermore, a specific user interface was created in the Visual Basic for Applications in this case study. The calculation parameters were set using this interface and optimization was started. During optimization, all columns were considered rectangular with dimensions of  $300 \times 300$  to  $500 \times 500$  mm with an increment of 50 mm (25 variants) and slabs thickness of 180 to 250 mm in increments of 10 mm (8 variants). In total, 200 combinations of load-bearing structures were calculated for one concrete strength class, reinforcement of columns and slabs was designed and CO<sub>2</sub> emissions were calculated together with the construction cost. The calculation of one such variant lasted for a relatively short time (approximately 6–7 seconds) and therefore it was possible to calculate all variants within given limits. For larger constructions or for a larger number of combinations, it would be necessary to use one of the numerical methods.



**Figure 2.** Average cost and CO<sub>2</sub> emissions of concrete per m<sup>3</sup>

The optimization of the load-bearing structure was performed for seven concrete strength classes (C20/25 to C50/60). These concretes are commonly available in the Czech Republic, and therefore it was not difficult to determine their average cost per 1 m<sup>3</sup>. The CO<sub>2</sub> emissions were calculated according to the content of cement in concrete, which accounts for more than 90% of emissions. These results are summarized in the line chart (Fig. 2). It is evident that the average cost (on the left axis) and CO<sub>2</sub> emissions (on the right axis) are increasing with a strength of concrete. A more significant increase of both these parameters can be seen between the strength classes C30/37 and C35/45 because for higher strength classes is required to use Portland cement CEM I with high clinker content instead of composite cements CEM II.

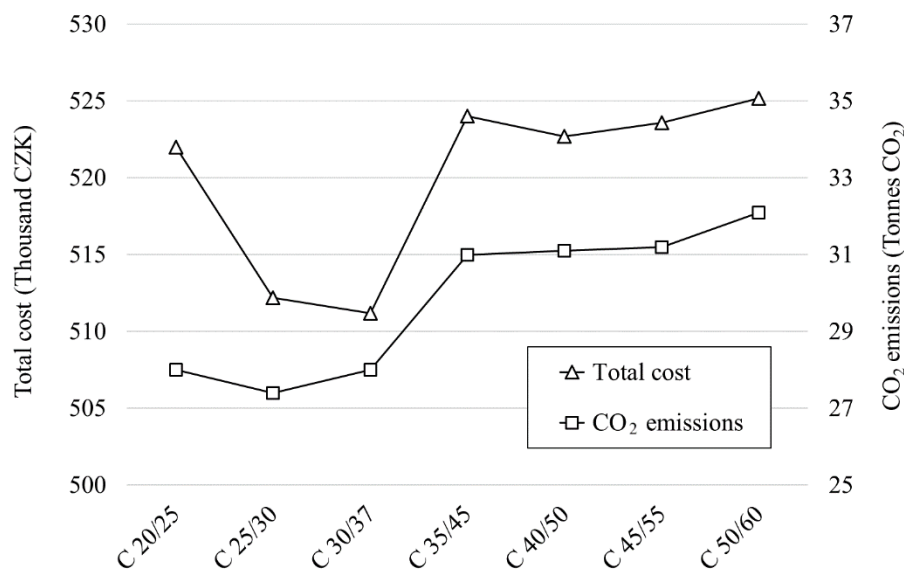
### 3.3. Results and discussion

The optimization results are summarized in the Table 1 and in the line chart (Fig 3). The optimal variant of the load-bearing structure was the one with minimum CO<sub>2</sub> emissions and construction cost (both variables were strongly correlated). The results show that concrete C25/30 is more advantageous to achieve minimal CO<sub>2</sub> emissions and concrete C30/37 for a minimal construction cost. However, as can be seen from the chart, the difference between the two concretes is only negligible.

**Table 1.** Summary of optimization results

Concrete strength class	Columns dimensions (m)	Slabs thickness (m)	Concrete volume (m <sup>3</sup> )	Steel weight (Tonne)	Greenhouse gas emissions (Tonne)	Total cost (Thousand CZK)
C20/25	0.3 × 0.45	0.24	56.4	5.50	28.0	522.0
C25/30	0.3 × 0.45	0.23	55.8	5.14	27.4	512.2
C30/37	0.3 × 0.4	0.23	55.3	5.00	28.0	511.2
C35/45	0.3 × 0.4	0.21	50.9	5.24	31.0	524.0
C40/50	0.3 × 0.4	0.2	48.7	5.26	31.1	522.7
C45/55	0.3 × 0.4	0.19	46.5	5.35	31.2	523.6
C50/60	0.35 × 0.35	0.19	46.6	5.21	32.1	525.2

Table 1 summarizes the optimum dimension of columns and slabs thickness for each concrete strength class. In the case of columns, only a small change in cross-section is visible because of the small height of the structure. Thickness of the slabs is already changing more significantly, from 190 to 240 mm. Slabs are dominant in terms of concrete consumption and constitutes approximately 90% of the volume of the load-bearing structure. The smallest volume of consumed concrete is therefore based on strength classes C45/55 and C50/60. On the other hand, their reinforcement required a greater amount of steel (see table) and this increase then negatively affected the total CO<sub>2</sub> emissions and the construction cost. This is due to the fact that the smaller thickness of slab also means a smaller lever arm of internal forces and hence greater force in concrete and reinforcement is necessary.

**Figure 3.** Total cost and CO<sub>2</sub> emissions of optimized construction

Slabs thickness, cross-section of columns, material transport, formwork or overall dimensions of the building, etc. all play a significant role in determining the optimal design variant. But there are other factors that can influence the choice of the optimal design variant. Probably the most important of them is the durability of the construction, which can be decisive for certain type of buildings. It can be expected that concretes of higher strength with longer durability will be favoured to the concretes with a lower strength.

#### 4. Summary

In the case study, the optimization of the load-bearing structure was demonstrated in order to reduce CO<sub>2</sub> emissions while maintaining the construction cost. Seven concrete strength classes (C20/25 to C50/60) have been compared for which the optimal variant of the load-bearing structure was obtained in terms of CO<sub>2</sub> emissions. The results showed that in this particular case the concrete C25/30 was the best in terms of CO<sub>2</sub> emissions and concrete C30/37 in terms of construction cost. Concretes of higher strength classes enabled smaller cross sections of concrete elements, however, concrete savings were not high enough in the particular case to compensate for higher CO<sub>2</sub> emissions and a higher cost for this concrete. One of the reasons is that smaller dimensions of bended structural elements lead to a reduction of the lever arm of internal forces which must be compensated by greater force in concrete and steel reinforcement. On the other hand, this case study did not consider the durability of concrete for example, which is certainly longer for concrete of higher strength.

Results of presented case study cannot be used as a generalisation for all structures. It would need analysis of much more cases in different boundary conditions. Nevertheless, it shows, that some simple decisions without detailed analysis, based on specific data and considering specific boundary conditions could result in wrong and not efficient solutions. More complex LCA would give more relevant picture about environmental impact of specific cases.

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