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Role of sequestration of CO₂ due to the carbonation in total CO₂ emission balance in concrete life

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Abstract

Calculation of the carbon footprint of cement concrete is a complex process including consideration of the phase of primary life (components and concrete production processes, transportation, construction works, maintenance of concrete structures) and secondary life, including demolition and recycling. Taking into consideration the effect of concrete carbonation can lead to a reduction in the calculated carbon footprint of concrete. In this paper, an example of CO₂ balance for small bridge elements made of Portland cement reinforced concrete was done. The results include the effect of carbonation of concrete in a structure and of concrete rubble after demolition. It was shown that important impact of carbonation on the balance is possible only when rubble carbonation is possible. It was related to the fact that only the sequestration potential in the secondary phase of concrete life has significant value.

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Keywords

Carbon footprint; Balance of carbon dioxide in nature; Concrete carbonation; The sequestration potential of concrete

Introduction: Balance of CO₂ in concrete life

Process of carbonation is usually considered in terms of negative influence on concrete properties and its durability, but it has also an ecological aspect - an advantageous one, taking into account the fact that the nature of the process is based on chemical binding of CO₂ absorbed from atmosphere (sequestration). Emission of CO₂ is one of the main components of the greenhouse effect. Thus, under certain conditions, carbonated concrete can be treated as a kind of air filter, which allows to slightly reduce the content of carbon dioxide gas in the atmosphere. Positive effect and its range are limited due to necessity of taking into account the negative influence of carbonation on structure durability and the fact that concrete has limited potential of bonding CO₂ per unit volume.

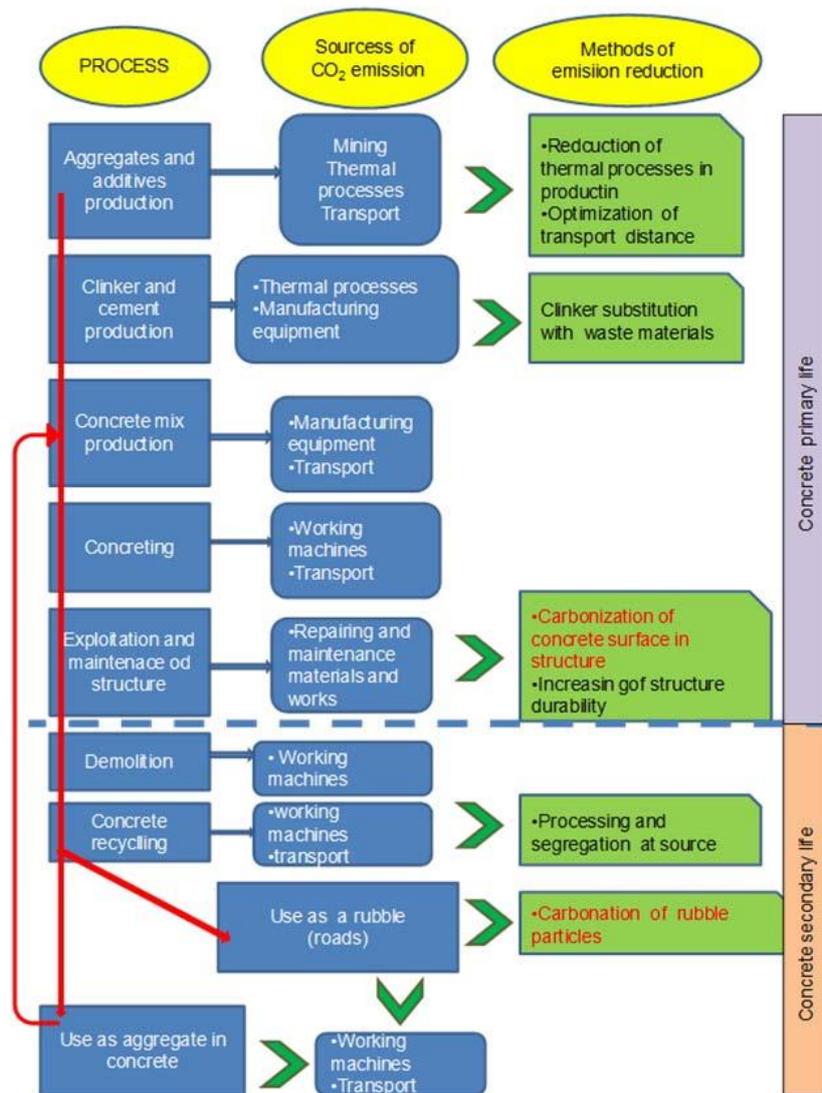


Figure 1 - Mapping nonlinear data to a higher dimensional feature space.

In the case of reinforced concrete structures, safe carbonation, and thus sequestration, or "capture and safe storage of CO₂" zone [1], because of the durability is the concrete cover. The amount of carbon dioxide that concrete can effectively bind, so-called sequestration potential [2], mainly depends on the calcium hydroxide content available in concrete for carbonation reaction. Concrete carbonation can be an element of carbon dioxide balance in the cement and concrete life cycle, affecting the assessment of the carbon footprint.

In accordance with ISO 14067 "Carbon footprint of products — requirements and guidelines for quantification and communication" [3] carbon footprint of product is a sum of greenhouse gas emissions and removals in a product system, expressed

as CO₂ equivalent and based on a life cycle assessment [3]. The carbon footprint of the product thus includes emissions from the mining raw materials from which it is produced, production, use and disposal or recycling after use [4]. Estimation of the carbon footprint of cement concrete is a complex process which needs to consider the phase of primary life including components and concrete production processes, transportation, construction works, maintenance of concrete structures as well as the secondary life, including demolition and recycling [5]. A full analysis of the

carbon footprint of concrete in the product life cycle (cradle to grave approach – Fig. 1) must also take into account the process of carbon sequestration by carbonation of concrete during its exploitation and in the secondary life [6].

The main quantitative source of CO₂ emissions in the life of concrete is cement production. The value of the emission of 0.7 tons of CO₂ per ton of cement [7] may be regarded as the output to determine the carbon footprint of cement and concrete in Polish national conditions.

The sequestration potential of concrete: case study

Consideration of carbonation in determining the carbon footprint of concrete requires the estimation of the amount of carbon dioxide that concrete can bind permanently as a result of carbonation. The quantity of CO₂ that can theoretically be bound in the concrete by carbonation is called the "CO₂ sequestration potential " and depends on inter alia: the cement content in concrete, the composition of the cement and cement clinker.

Assuming that 1 kg of fully hydrated Portland cement is the source of about 0.3 kg of Ca(OH)₂ and typical level of hydration of cement in concrete does not exceed 93%, it can be calculated that each kilogram of Portland cement clinker is able to bind approximately 0.17 kg of CO₂. Taking into account the clinker content in Portland cement (usually ca. 95%) and cement content in concrete, sequestration potential of concrete $S_{CO_2^{bet}}$ can be calculated as follows:

$$S_{CO_2^{bet}} = S_{CO_2} \cdot P_{cl} \cdot C \text{ (kg/m}^3\text{)} \quad (1)$$

Where, S_{CO_2} is clinker sequestration potential in kg/kg, P_{cl} is clinker content in cement, and C is the cement content in concrete, kg/m³.

Calculation (1) is valid only for Portland cement concrete. The use of mineral additives like fly ashes and slag in cement or concrete, needs to be included in (1) a coefficient, which considers a decreased amount of calcium hydroxide due to pozzolanic reaction. The computationally or experimentally determined value of the potential sequestration of concrete can be used in the calculation of the carbon footprint in the life cycle of cement or cement concrete. Consideration of the CO₂ sequestration potential resulting from the carbonation of concrete could therefore improve the unfavorable balance of emission and absorption of carbon dioxide in the life cycle of cement concrete [8-10].

Considering the carbonation of concrete as one of the possibilities of CO₂ sequestration, the other effects of this phenomenon should be regarded. While any amount of absorption of carbon dioxide harmful excess from the air is positive and expected, it also constitutes a danger to reinforced structure durability due to the limitation of the concrete cover passivating functions. The sequestration of CO₂ by concrete carbonation in the structure is possible with no negative effect for durability only in the surface layer, the thinner concrete cover, which protects the reinforcement against corrosion.

The results of the author's former research [2] confirmed that the carbonation process can be considered as a process limited in time. However, analysis of the results enabled the author to claim that the finite carbonation depth in concrete, h , could be described according to:

$$h = B + A \cdot t^{-0.5} \quad (2)$$

Moreover, the maximum depth of carbonation is limited by the asymptote described by (3):

$$\lim_{t \rightarrow \infty} h(t) = B \quad (3)$$

The above equations can be the basis of designing the safe value of concrete cover thickness, also considered as an atmospheric CO₂ sequestration zone that does not negatively influence the potential time of structure life.

Assuming that during designed service life (e.g. 50 or 100 years) the carbonation depth reaches the value very close to h_{max} , calculation of the amount of carbon dioxide sequestered $S_{CO_2}^{konstr}$, in the concrete volume V_B in construction can be carried out using a model of hyperbolic carbonation, according to:

$$S_{CO_2}^{konstr} = S_{CO_2}^{bet} \cdot h_{max} \cdot P(kg) \quad (4)$$

Where, $S_{CO_2}^{bet}$ is concrete sequestration potential, calculated with (1); h_{max} is maximum depth of carbonation, in accordance with (3), and P is carbonated concrete surface in structure (not protected with other materials). In addition to a complete balance of sequestration, the effect of concrete carbonation of concrete rubble can be added, if it is stored in the form and conditions that allows carbonation.

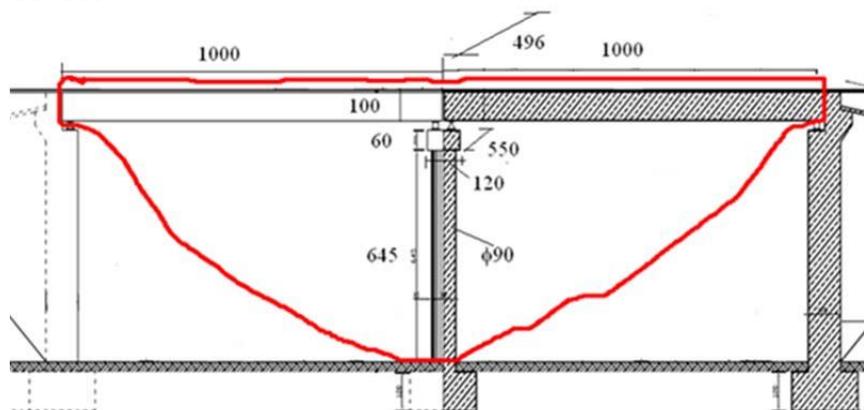


Figure 2 - Dimensions of analyzed part of concrete bridge

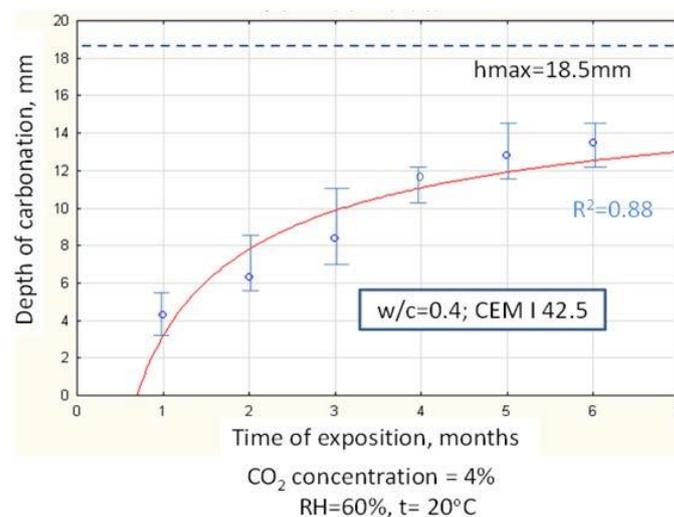


Figure 3 - Experimentally developed model of carbonation (general formula according to (2) for concrete used in the analyzed case).

The depth of carbonation depends strongly on CO₂ concentration and it is not easy to describe this effect with mathematical formula; however it could be estimated that, measured depths of carbonation h_{max} in two different concentrations (c1, c2) after two different times of exposure (t1, t2) is the function of square root of this concentrations ratio if other testing conditions are the same [13-17].

$$\frac{h_{max,t1,c1}}{h_{max,t2,c2}} = \frac{t1}{t2} \cdot \sqrt{\frac{c2}{c1}} \quad (5)$$

This relationship is only truthful for a limited range of CO₂ concentrations, up to a few or several percent. With higher values of the concentration of CO₂, the carbonation process changes its nature. Due to the higher CO₂ concentration, some other hydration products (not only calcium hydroxide) are involving strongly in the carbonation reactions. Formula (5) could be used for predicting the maximal depth of carbonation (asymptote value) in natural conditions on the basis of experimental results of testing in standard conditions (1% or 4% concentration of CO₂). In the analyzed case c1=4% (CO₂ concentration during accelerated testing), c2=0.04% (typical concentration of CO₂ in atmosphere), t1=210 days (time of exposure in accelerated conditions), t2=100 years =36500 days (time of expected service life i.e. time of exposure in natural conditions). By inserting into (5) the value $h_{max,c1,t1}=18.5$ mm (obtained experimentally – Fig. 3) and other abovementioned data, $h_{max,c2,t2}$, could be calculated as:

$$\frac{18.5}{h_{max,t2,c2}} = \frac{210}{36500} \cdot \sqrt{\frac{4}{0.04}} \quad (6)$$

$$h_{max,t2,c2} = 32 \text{ mm} \quad (7)$$

The value 32 mm is the expected maximal depth of carbonation of concrete used in the analyzed case after 100 years of exposure in natural conditions.

Taking into account the geometry of the structure and the sequestration potential of Portland cement clinker (0.17 kg CO₂/kg clinker), sequestration in the *primary life* of concrete was calculated, and then sequestration in the *secondary life* (for particles size of rubbles: 2. $h_{max} = 64$ mm) was calculated in Table 1.

Table 1 - The calculation of carbon sequestration in the life cycle study of a section of concrete viaduct

Concrete volume, $V_c = 62 \text{ m}^3$; Concrete carbonate surface, $S_c = 212 \text{ m}^2$	Kg CO ₂
Emission of CO ₂ during production of concrete ingredients	
Cement	17794
Aggregate Granite	2827
Others	3
Sum	20624

Emission of CO ₂ during transportation of concrete ingredients	
Cement	620
Aggregate granite	1736
Others	186
Sum	2542
Emission of CO ₂ during production, transport, and concreting	248
TOTAL EMISSION	23414
<i>Carbon sequestration in the primary life of concrete, $S_{CO_2}^{Konstr}$</i>	450
<i>Carbon sequestration in the secondary life of concrete, $S_{CO_2}^{rec}$</i>	3640
BALANCE	19324

Discussion and Conclusion

Concrete carbonation can lead to a reduction in the carbon footprint of cement by more than 20% (Fig. 4). It should however be noted that the importance of carbonation of concrete structures in the overall balance is marginally small.

In the analyzed case, the concrete in the structure can absorb about 0.45 tons of CO₂ which is only about 2% of total emissions (Table I). This value is very small even though the analyzed structure characterizes by a relatively high ratio of surface subjected to carbonation in to the volume of the concrete in the structure. Yet, there are other more effective ways with high CO₂ absorption rate for the synthesis of environmental concrete chemical admixture. In addition, carbon footprint reduction can be achieved by adjusting the waste recycling process or the use of renewable materials. These new environmental technologies have proven applications in other industry rather than construction as well [18-39].

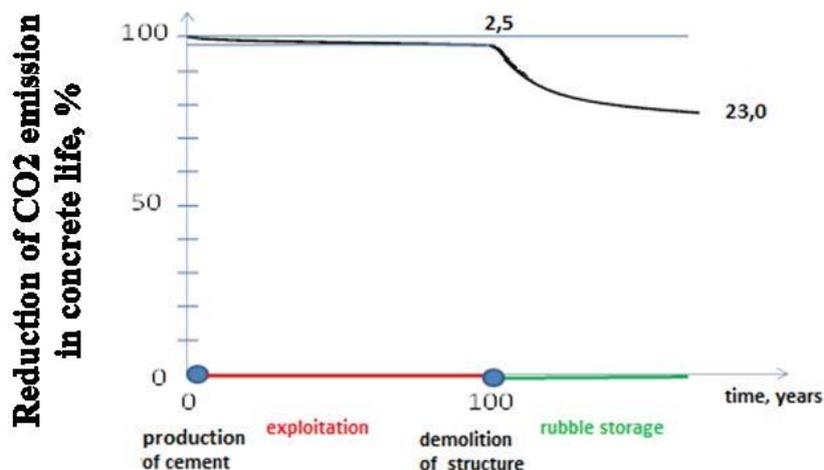


Figure 4 - CO₂ balance in the life of the concrete used on the analyzed structure.

The example shows the important role of carbonation in the balance of emissions and absorption of carbon dioxide in the lives of cement and concrete if there is a possibility of concrete rubble carbonation after demolition of the structure. The share of primary life concrete carbonation may be important in

the balance of CO₂ for the construction with a very large carbonated surface.

The effective role of sequestration of CO₂ by carbonation in the carbon footprint calculation has to be considered for a specific structure, and above all, the rubble recycling scenario has to be predicted, because the sequestration potential in the secondary phase of concrete life can have an important impact on the balance effect.

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