Decrease of Cement Production Environmental Burden – LCA

A Horáková, H Schreiberová, I Broukalová and J Fládr
Department of Concrete and Masonry Structures, Faculty of Civil Engineering, Czech Technical University in Prague
anna.horakova@fsv.cvut.cz

Abstract. A big progress has been made in decrease of environmental impacts of cement production. Dust pollution around cement plants has been considerably decreased thanks to efficient dust separators. An intention of further emission reduction has been announced. The environmental burden of cement production is also decreased by substitution of cement by alternative binders. Hydraulic properties of energy by-products have been investigated for a long time to check their potential as a partial substitution of traditional cement binder. The paper will focus in examining the influence of variation of the concrete composition on the environmental impacts, identification of the most severe procedures in the cement production and analysis of meaningfulness of implementation of the proposed measures. The environment is a complex system. Potential modifications of concrete composition or production technology may bring benefits in certain areas and on the contrary cause environmental harm from another perspective. Hence, analysis of the cement production impacts cannot be based on one aspect, and a broad portfolio of impact categories will be assessed regarding concrete production environmental burden.

1. Introduction
In recent decades, the rising global population and further increasing needs for urbanization and infrastructure have led to a more detailed exploration of the development sustainability. Concrete, as the most widely used man-made material, has a great impact on the social, economic and environmental pillars of sustainable development. The cement production is the third-largest industrial energy consumer with 7% of the global industrial energy use 10.7 EJ and the second largest producer of total direct industrial CO2 emissions at 27% in 2014 [1]. Furthermore, an increase of the cement production can be expected in future decades. Thus, a variety of adjustments of the traditional approaches is inevitable for preserving natural resources and ecosystem services upon which the economy and society depend.

To improve the environmental, economic and possibly technical properties of the cement-based materials, a part of cement has been successfully substituted with fly ash for decades. This by-product of coal-burning thermal power stations has been used since 1930. At first, it was applied for a reduction of the heat generation in massive structures [2–4]. However, subsequent research has shown other beneficial aspects of using fly ash as a cement substitution: improved workability and long-term strength, reduced permeability, minimized risk of alkali-silica reaction, and enhanced durability performance by improved resistance to chloride and sulphate attack [5–9].

Previous studies proved that replacement of cement with fly ash leads to a reduction of total CO2 emissions [10] and energy consumption [11]. However, it is important to note that the evaluation of the environmental impacts of concrete with fly ash is not a straightforward problem. As fly ash is a by-
product of electricity production, the process is multifunctional. It implies that the electricity cannot be produced separately from fly-ash when burning coal. This leads to problematic attributions of environmental impacts on the production of electricity and fly-ash independently [12]. Nevertheless, it is clear that an exploitation of the waste product as a partial replacement for cement is a step towards more sustainable construction.

The combustion of coal used in power plants is not an ecological process itself. Sulfur oxides, particulate matter and nitrogen oxides (NOx) are the key combustion-generated air contaminants [13]. Nitrogen oxides, especially, are considered as the primary pollutants of the atmosphere. They have been associated with numerous environmental effects such as acid rain, photochemical smog, tropospheric ozone layer depletion and even global warming [14]. For that reason, more rigorous environmental laws are introduced. In relation with the modification of European Union legislation (Directive 2016/2284/EU) lower emission limits of nitrogen oxides and other substances except for sources are from 1.1.2016 applied.

To reduce emissions of NOx, various methods are available. It is possible to either reduce the NOx formations during the combustion process [15] or apply certain post-combustion control methods [13]. Such techniques involve selective catalytic reduction (SCR) [16,17], selective non-catalytic reduction (SNCR) [18], thermal DeNOx and scrubbing [13]. The most commonly used methods, SCR and SCNR, are based on reactions between nitrogen oxides and ammonium/urea which lead to the production of nitrogen and water vapor [19]. SNCR takes place at higher temperatures, 900–1000°C, without a presence of a catalyst. SCR can occur at lower temperatures around 300–400°C thanks to the presence of the catalyst. SCR can occur at lower temperatures around 300–400°C thanks to the presence of the catalyst [20]. Although SCR reaches higher efficiency, SNCR has been preferred due to high investment and operating cost of the SCR method [13].

Till this day, not enough research has been done to gain deeper knowledge about the impact of the addition of ammonium or urea to the quality and usability of the combustion process by-products. It is known, that the surplus ammonium from the reactions with NOx leads to a formation of ammonium salts which are then concentrated in the produced fly ash. When the fly ash is later used as a substitute for cement in concrete, the present ammonium salts react with the alkaline components. This reaction leads to the release of gaseous ammonia – a very toxic compound which is dangerous for the environment [20].

Additionally, the spherical shape of the fly ash grains has a positive impact on the cement paste rheology. However, the desired shape is mainly caused by a high combustion temperature and gradual cooling. In the case of SCNR, a sudden temperature change occurs when the reducing agent is dispersed directly to the hot combustion chamber. This temperature shock then results in a change of the grain morphology which affects the rheology of fresh cement paste [21].

As a consequence, the presence of residual ammonium and the negative impact on the grain shape cause limited possibility of exploitation of the fly ash in concrete structures. Thus, the question is whether the positive impacts of NOx reduction on the environment could outweigh its negative effects, such as the potential environmental hazard and accumulation of the waste products. Furthermore, the exploitation of the waste product in concrete production has been proved to lower CO2 emissions and energy consumption.

For that reason, the aim of this paper is to develop and a quantified life cycle assessment (LCA) model. This LCA model is then used to evaluate various environmental impacts of the fly ash exploitation and its production process, with and without the NOx reduction method. The obtained results could further serve as a basis for optimization of the NOx reduction process during coal combustion with regard to positive impacts of fly ash exploitation in concrete.

2. Methods

As previously stated, the evaluation of the fly ash exploitation in concrete in terms of environmental impacts was performed using Life-cycle assessment (LCA) according to relevant standards [22]. The LCA technique is usually based on the whole life-cycle of the investigated product or at least its significant part. Thus, the assessment includes obtaining raw materials, their transport to the place of processing, manufacturing of the final product, use of the product and further maintenance or repairs if
necessary, and final disposal of the product. In some cases, however, the prediction of the course of the phase of use is not possible and the evaluation includes only a chosen part of the life cycle. The assessment used in this paper was applied to concrete as a material for further use. Hence, it included the phase of obtaining of raw materials, their transport and processing and manufacturing of the final product.

At first, the consumption of raw materials and emissions released into the environment were defined for each interproduct such as cement, aggregate, water, fly ash and superplastizer. Within the assessment, the most significant environmental impacts were considered: consumption of raw materials, global warming and climate change, acidification and eutrophication of the environment, stratospheric ozone depletion, photooxidant formation, and human health. In LCA, these environmental impacts are called impact categories.

The environmental impacts of each interproduct were calculated. Impacts on the environment were quantified by so-called impact category indicators – measurable variables that can be used to observe changes in the environment. The values indicate the extent of environmental damage caused by human activities. Usually, the impact category is influenced by various of substances where some substances are very harmful, and some less. Thus, all the substances are converted to an equivalent amount of the reference substance (for example carbon dioxide for global warming and climate change or sulfur dioxide for acidification of the environment).

The effect of a specific substance to each impact category was determined by so-called characterization models. A characterization model for a specific impact category is a set of values that reflect the ability of various substances damage the environment within the impact category. All of the issued substances are converted to the equivalent amount of a reference substance by using these values (characterization factors – CF). This paper used a characterization model which is recommended in Product category rules (PCR) for concrete products [22]. The resultant impact category indicator was calculated according to the following relationship:

\[ V_{XY} = CF_{1,XY} \cdot \Sigma m_{1i} + CF_{2,XY} \cdot \Sigma m_{2i} + ... + CF_{n,XY} \cdot \Sigma m_{ni} \]  

(1)

where \( V_{XY} \) is a result of the impact category indicator (XY indicates the impact category), CF is a characterization factor and m is an amount of a released substance.

When evaluating the impact categories, emissions of following substances were 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 sulfide \( H_2S \), ammonia \( NH_3 \).

In this paper, three material variants in the amount of 1 m³ were compared (Table 1). The first variant (CEM) was conventional concrete containing only cement as a binder. In this variant, no NOx reduction method was used. The second variant (CEM–SNCR) was also conventional concrete with the cementitious binder only, but NOx reduction method was used. The variant CEM–SNCR was included in the model to simulate the impossibility of the fly ash exploitation due to the NOx reduction processes. For the evaluation of the NOx reduction, the most often reported value of efficiency of this method is 40–70 %. Therefore, the value of 55 % was considered.

In the third concrete recipe (CEM–FA), fly ash was used as a partial substitution for cement. In this variant, no NOx reduction process was applied.
Table 1. Concrete mix designs considered in the LCA evaluation.

|                | CEM    | CEM-SNCR | CEM–FA |
|----------------|--------|----------|--------|
| Cement [kg/m³] | 800.00 | 800.00   | 560.00 |
| Fine aggregate [kg/m³] | 730.00 | 730.00   | 730.00 |
| Coarse aggregates [kg/m³] | 710.00 | 710.00   | 710.00 |
| Water [kg/m³]  | 210.00 | 210.00   | 172.20 |
| Fly ash [kg/m³] | 0.00   | 0.00     | 240.00 |
| Superplasticizer [kg/m³] | 32.00  | 32.00    | 29.52  |
| NO₅ reduction  | –      | SNCR     | –      |

3. Results
The results of the sustainability assessment were related to the specific environmental impacts: global warming potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical oxidant creation potential, human toxicity potential and element and fossil abiotic depletion potential.

The results from the conducted LCA showed that the concrete mix design with a fly ash addition (CEM–FA) reached the lowest values in the majority of the inspected environmental impacts. Only in the case of eutrophication potential, the impact of the concrete mix design where NO₅ reduction was included (CEM–SNCR) reached the lowest value as it can be seen in Figure 3. Nevertheless, the addition of fly ash still had a positive impact on this category.

The results indicate that the SNCR process had only an insignificant impact on global warming potential (Figure 1) and photooxidant formation (Figure 5). The acidification (Figure 2) and human toxicity potential (Figure 6) was slightly improved by the NO₅ reduction process when compared to the traditional concrete design (CEM). However, the fly ash addition (CEM–FA) still proved to have a more noticeable positive effect.

The emissions of NO₅ have no impact on the categories of stratospheric ozone depletion (Figure 4) and the consumption of raw materials (Figure 7 and Figure 8). For that reason, the impact values of CEM–SNCR and CEM were identical.

In Figure 9, the investigated different approaches to reduction of environmental impacts are compared to non-treated concrete (CEM). It can be clearly seen that the addition of fly ash (CEM–FA) caused a significantly larger reduction of the environmental impacts in all of the categories except for the eutrophication potential, where the SNCR process proved to be more efficient.

Figure 1. Comparison of global warming potential (GWP).

Figure 2. Comparison of acidification potential (AP).
Figure 3. Comparison of eutrophication potential (EP).

Figure 4. Comparison of ozone depletion potential (ODP).

Figure 5. Comparison of photochemical oxidant creation potential (POCP).

Figure 6. Comparison of human toxicity potential (HTP).

Figure 7. Comparison of abiotic depletion potential (ADP) element.

Figure 8. Comparison of abiotic depletion potential (ADP) fossil.
4. Discussion
According to the evaluations presented in this paper, a partial replacement of cement with fly ash was a more favourable sustainability improvement measure over the NO\textsubscript{x} reduction process. The SNCR process only improved the eutrophication to a greater extent. As the NO\textsubscript{x} emissions play a major role in the eutrophication, this result was expected.

The limited impact of the NO\textsubscript{x} reduction on the global warming potential and photooxidant formation was also in agreement with the expectations. Both of these categories are capitaly influenced by the cement production. As CEM and CEM–SNRC had the same dosage of cement, the results were not expected to differ significantly.

5. Conclusion
The results presented in this paper show that a partial replacement of cement with fly ash decreases consumption of raw materials and significantly reduces emissions of harmful substances. Although not that extensively, the application of SNCR reduces the majority of the environmental impacts as well. Compared to the fly ash substitution, the NO\textsubscript{x} reduction largely affects the eutrophication of the environment.

As previously mentioned, the NO\textsubscript{x} reduction technologies used during the combustion process negatively affect fly ash in terms of grain morphology and chemical composition. Thus, they endanger the further exploitation of the fly ash in concrete production, resulting in accumulation of unusable material. Based on the assessment presented in this paper, replacement of the cement with fly ash seems to positively interfere with more of the environmental impact categories than the investigated NO\textsubscript{x} reduction process.

Results from this paper indicate that partial replacement of cement, the highly energetically demanding material, with untreated fly ash could be a more efficient approach to sustainable development. However, the SNCR method may be more advantageous in locations where eutrophication of water and soil is the main environmental problem.

![Figure 9. Percentage reduction of environmental impacts: global warming (GW), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical oxidant creation potential (POCP), human toxicity potential (HTP), abiotic depletion potential (ADP), fossil and element. Comparison of SCR method (CEM–SCR) and the addition of fly ash (CEM–FS).](image-url)
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