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Carbon footprint analysis of calcined gypsum production in the Czech Republic

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ABSTRACT

Sustainable development efforts aimed at substantial reduction of carbon dioxide emissions focused research activities in this field, among others, on a partial or full replacement of Portland cement by environmental more friendly alternatives. Calcined gypsum can be considered as one of possible options in that respect. However, although the environmental impact is an important issue, gypsum was analyzed only rarely and sufficiently accurate data are still missing. In this paper, a carbon footprint analysis of two types of gypsum ranging from cradle to gate according to ISO 14067 is presented. The inventory data based on primary data obtained from the producers of natural gypsum and flue gas desulfurization gypsum in the Czech Republic are completed by the emission factors obtained from the literature survey. The results of the carbon footprint analysis show that the carbon dioxide emissions related to the manufacturing of calcined gypsum from flue gas desulfurization gypsum are 105.3 kg of carbon dioxide/t, i.e., 25.2% lower than for the application of natural gypsum. Calcination is identified as the most harmful process from the point of view of carbon dioxide generation for both raw materials; it is responsible for 55% and 72% of total carbon dioxide emissions for natural gypsum and flue gas desulfurization gypsum, respectively. The obtained information is essential for further design and development of new types of composites meeting the requirements of sustainable development better than today's mainstream solutions.

1. Introduction

The growth of human population accompanied with a fast development of industry and transportation in some parts of the world during the last several decades brought new challenges to the human society. The threat of acceleration of global warming led to a greater concern on anthropogenic carbon emissions and their influence on the global climate. In the light of concerns associated with the depletion of fossil fuels, excessive energy consumption and consequent increase of concentration of carbon dioxide in the atmosphere, the sustainability principles became more important (Mikulčič et al., 2016). The importance of preservation of environmental conditions intensified the efforts aimed at the achievement of sustainable development principles, thus mitigation of negative externalities of human activities (Dincer, 2000; Panwar et al., 2011). From this point of view, the building industry can be perceived as one of the main sources at the generation of emissions having negative impact on the environment (Bigerna et al., 2017). However, contrary to some other industrial and transportation sectors, where great efforts towards a substantial decrease of carbon dioxide emissions were already exerted successfully, the manufacturing processes of many building materials cannot be considered yet as satisfactory from an environmental perspective (Bains et al., 2017; Requia et al., 2017).

Carbon dioxide emissions related to cement production (Uwasu et al., 2014; Cai et al., 2008) belong to the highest among building materials. According to the data of the International Energy Agency (IEA, 2008), the production of cement is responsible for ~8% of world carbon dioxide emissions. The calcination process and heating to desired temperatures generate, in average, 0.81 kg of CO_2 per 1 kg of cement (Chen et al., 2010). In addition to the harmful effects on the environment, cement production may also present risks to the human health. The investigations of Garcia-Perez et al. (2015) revealed a higher potential risk of dying from cancer in the 50-km radius from industrial activities, such as lime or cement manufacturing. Negative human health consequences related to

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the cement use (exposure to allergens, free crystalline silica, or hexavalent chromium) pose a serious risk as well (Moretti et al., 2017). Therefore, new strategies leading to limitations of negative impacts of cement production were formulated (Summbell et al., 2016) and new approaches aimed at progressive and advanced techniques (Valderrama et al., 2012) or at the substitution of fuel base (Fyffe et al., 2015; Rovira et al., 2010) were developed lately. However, the barriers related to a longtime payback of invested capital, short-run decision, and mistrust to the application of unproven technologies still present the main limits to the application of more efficient innovations in the cement industry (Chen, 2009; Pardo et al., 2011).

Utilization of materials with lower energy demanding production, which could partially replace Portland cement in binders, can be considered as one of the prospective ways towards mitigation of environmentally harmful effects related to cement manufacturing (Turk et al., 2015). Slag (Rosales et al., 2017), fly ash (Hannesson et al., 2012), or sewage sludge (Pavlík et al., 2016) can be mentioned as characteristic examples in that respect. Another alternative can be found in a complete replacement of Portland cement by a different material base, at least in some practical applications. Here, calcined gypsum or geopolymers belong to the most prospective solutions.

The availability of raw gypsum on the market is relatively wide at present, the main sources being natural gypsum quarried in certain locations and various types of waste gypsum appearing as by-products of some industrial activities, e.g., flue-gas-desulfurization-, phospho-, titano-, and boro-gypsum. However, despite the long history of its use, gypsum finds currently only a limited application in the building industry, mostly in the form of plaster boards or interior plasters. Its potential for future applications is though much greater, e.g., as a material of load-bearing structures (Tesárek et al., 2007) or lightweight construction material with properties similar to cellular concrete (Vimmrová et al., 2011).

The positive effects of gypsum application in construction on the environment were recognized already years ago, but mostly it was on a general level only. For instance, Guo and Shi (2008) concluded that the production of gypsum is less demanding on energy inputs due to the lower temperature of raw material calcination, and the carbon dioxide emissions related to the raw material decomposition are also reduced. Suaréz et al. (2016) referred to significant savings achieved by the utilization of waste gypsum. The lower decomposition temperature accompanied with decreased energy consumption was used by Ling and Kwan (2016) as a supporting fact of their research.

The analyses of the environmental impact of gypsum production published to date were relatively rare and mostly suffered from the lack of primary data. Jimenéz-Rivero and García-Navarro (2016) in one of the very few studies on gypsum life cycle used therefore generic data derived from the case studies on similar building materials. The problems related to the absence of primary data were though noticed also for the most frequently analyzed building materials, such as concrete (Dong et al., 2015). The results on the evaluation of environmental impact of Portland cement found in the scientific literature can serve as another example in that respect, they varied from 662 kg (Deja et al., 2010) to 950 kg (Ali et al., 2011) of CO_2/t. Dong et al. (2015) assigned the lack of primary data on concrete partially to the unwillingness of industrial subjects to provide real data about environmental impacts of their main operating activity. However, some more objective factors, such as purity of the raw material, used technology, transportation, and other regional particularities (Zhang and Wang, 2016) can play an important role as well. Therefore, in order to provide a comprehensive overview of environmental impacts, the local factors, such as composition of the energy mix, fuel base, manufacturing technologies and efficiency, the legal framework, and composition of the raw materials should be taken into account (De Wolf et al., 2017; Heidari et al., 2017).

In this paper, the environmental assessment of calcined gypsum production in the Czech Republic is presented. The analysis includes two major sources of raw gypsum, namely natural gypsum and flue gas desulfurization (FGD) gypsum; the minor gypsum sources, such as titanogypsum, phosphogypsum, or fluorogypsum, are not considered. The carbon footprint related to calcined gypsum manufacturing is determined for both types of raw gypsum and compared with Portland cement. Contrary to some previous studies published by other investigators, the calculations are based on primary data obtained from the particular producers, and the regional factors are taken into account.

2. Materials

2.1. Natural gypsum

Natural gypsum is the primary source for the production of sulfate binders in the country. The Kobeřice quarry located in the northeast (Silesian) part of the Czech Republic represents its exclusive source. The beginning of mining dates back to 1965. The area of quarry reaches 65 ha and the thickness of gypsum layer is about 35 m. The raw material contains 60–85% of calcium sulfate dihydrate with an admixture of clay and small amount of anhydrite. A detailed composition of mined rock is given in Table 1. The gypsum was formed by sedimentation in a closed water bay. Initially, together with fine particles, the gray-colored lower benches, which contain about 50% micro- and macro crystalline gypsum, gradually settled. Later, the upper level was characterized by coarser crystals with a higher gypsum content of up to 90%. The last layer, overburden, is made up of only 60% by gypsum and the rest are clays, loess, and humus loams.

Material processing starts in the quarry by mining of the raw material and ends after the production of gypsum hemihydrate (Fig. 1). Gypsum extraction methods are based on the utilization of stall mining procedures, such as drilling and rock blasting. Exhausted materials are consequently loaded on trucks and taken away to the first stage of screening to remove mudstone and other undesirable content. Afterwards, the material is crushed, finely grounded, and placed into the stock, where it is naturally pre-dried. After a certain time period, depending on the intensity of the mining, the material is moved by the belt conveyors toward the calcination furnace using natural gas as fuel. Currently, the modernized kiln with utilization of the residual waste heat provides about 5–10% fuel consumption savings compared to the outdated kiln used in the previous period. The fired gypsum is further moved by belt conveyors, milled to fine particles and moved to the final storage. Currently, the production of natural gypsum is

Table 1
Mineralogical and oxide composition of the natural gypsum rock.

Component	Amount (mass %)
$CaSO_4 \cdot 2H_2O$	60–80
$CaSO_4$	<0.5
Water	<10
Loss of ignition	<16
SiO_2	8–16
SO_3	28–37
CaO	24–36
MgO	0.2–1
Al_2O_3	<1
Fe_2O_3	<1.6