Life cycle assessment of the use of sewage sludge as Portland cement replacement

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Abstract. In this paper, we proposed an alternative thermal treatment of sewage sludge, aimed at its application in blended cements, which can reduce the energy demands and requires less technologically sophisticated processing. The life cycle assessment (LCA) was performed to quantify the environmental impact of the sewage sludge used as a partial cement replacement. The LCA was focused on the CO₂ emission and energy consumption. The functional unit of 1 m³ of blended mortars composed of Portland cement CEM I 42.5, silica sand, and thermally treated sewage sludge, where the sludge was used as partial cement substitute in a dosage of 10, 20, and 30% by mass of cement, was analyzed. The positive effect of the use of sewage sludge as a partial cement replacement with respect to the energy consumption and GHG emission, considering the compressive strength of the analyzed composites, was quite apparent. The decrease of energy consumption necessary for the production of the analyzed blended binders was nearly 10% per each 10% of sewage sludge used as Portland cement replacement. The energy needed for the sludge thermal treatment at 700°C was 220 MJ/t. The emission of GHG related to the sludge thermal treatment was 40kg/t. The presented data were strongly affected by the applied distribution of electricity sources, with a high share of coal combustion plants.

1. Introduction
The sewage sludge originating from the municipal wastewater treatment plants is produced in large quantities all over the world. Due to the rapid progress in urbanization and industrialization, which is characteristic for the developing countries, a high increase in the production of sewage sludge could be observed over the last several decades [1]. Sewage sludge must be processed in an appropriate way, because it frequently poses a threat to the natural environment resulting, for instance, from high heavy metal content [2]. Deposition of sewage sludge in landfills and its application in agriculture were limited through the regulations issued by the European Union [3-6]. Currently, the most common method of sewage sludge disposal is still landfilling, and in some countries also disposal into the ocean. Moreover, it is partially applied in agriculture, for example as organic fertilizer and for the soil management [7]. However, in that case of disposing, it must always be considered that sludge contains pollutants and unstable pathogens which can present potential health and environmental hazards. Therefore, the sewage sludge landfilling will become inapplicable in a near future and other methods of sludge disposal must be searched. These alternative methods may consequently lead to the recovery of valuable raw materials.
from potentially dangerous materials, processing them in order to enable their use in agriculture, various branches of industry or heat and energy recovery.

Due to the high carbon footprint of cement production, different types of mineral admixtures were tested up to now as possible PC (Portland cement) substitutes. There are two aspects of cement production that result in emissions of CO$_2$ [8]. The first is the chemical reaction involved in the production of the main component of cement, clinker, as limestone is decomposed by the addition of heat [9]. According to recent estimation, these so-called “process” emissions contribute about 5% of total anthropogenic CO$_2$ emissions excluding land-use change. The second source of emissions is from the combustion of fossil fuels used for heating raw clinker ingredients up to melting temperature [10]. Total emissions from the cement industry could therefore constitute as much as 8% of global CO$_2$ emissions [11-14].

Supplementary cementitious materials became quite common in today’s concrete industry [15], [16]. Typical examples are by-products of iron, silicon and ferrosilicon alloys production, and waste products from coal combustion in thermal power stations. Here, blast furnace slag, fly ash and micro silica are produced. At present, these products are commonly applied in concrete production, and their beneficial effects on concrete properties and performance are proven by many years of usage. However, there is still number of other pozzolana materials that are applied in blended binder and concrete production very rarely, and which contribution to concrete performance is not yet fully understood [17]. Therefore, we proposed an alternative thermal treatment of sewage sludge in this paper, aimed at its application in blended cements, which can reduce the energy demands and requires less technologically sophisticated processing.

2. Materials, characterization, conducted tests

2.1. Sewage sludge processing, composites preparation
The fermented and mechanically dewatered dried sewage sludge from wastewater treatment plant located in Lublin, Poland, was thermally treated for 2h at 700°C. The temperature of thermal treatment was chosen based on previous sludge TG/DSC analysis [18]. The produced sewage sludge ash (SSA) was mechanically activated by milling to the fineness similar to cement.

The composites (mortars) were prepared from OPC CEM I 42.5 R. As fine aggregate, silica sand of fraction 0–2 mm was used. It is a product of Filtrační písky, Ltd., Chlum u Doks, Czech Republic and it was mixed from three sand fractions. The weight ratio of sand fractions was 1:1:1. In mortars composition, OPC was partially substituted with SSA; its dosage was 10, 20, and 30% of cement mass. The water-binder ratio of 0.5 and the sand-binder (cement + SSA) ratio of 3.0 were constant for all composite mixes. Control mortar composed of OPC, sand, and batch water was also produced. The fresh mixes were casted into 40mm × 40mm × 160mm iron molds and after 1 day demolded, and cured in water at a temperature of (21 ± 2)°C. The characterization of mortar samples was conducted for samples matured for 28 days.

2.2. Experimental stage
The performed tests included measurement of basic structural properties of the developed mortar and their compressive strength. Among fundamental structural properties of researched mortars, bulk density, specific density, and total open porosity were measured. Before these tests, the specimens were dried in a vacuum drier at 60°C. The specific density $\rho_s$ (kg/m$^3$) was measured using helium pycnometry. The bulk density $\rho_b$ (kg/m$^3$) of mortar specimens was determined according to the EN 1015-10 (2000) [19] using a gravimetric method. The expanded combined uncertainty of the bulk density test was 1.2%. The total open porosity $\psi$ (%) was calculated from the known bulk density and matrix density values with combined uncertainty of 1.7% [20]. The compressive strength test was conducted according to the EN 1015-11 standard (1999) [21]. The loading area was 40mm × 40mm. The relative expanded uncertainty of strength test was 1.4%.
3. LCA analysis

In order to determine the environmental impact of the use of SSA in blended mortars, two basic comparative criteria were chosen, namely carbon footprint and the amount of consumed energy. A functional unit of 1 m³ of final material and additional functional units as 1 t of cement and 1 t of SSA were used in calculations. The range of the analysis was reduced to the intermediate stage of material processing, i.e., the material production consisted basically of two main subsystems, namely production and processing of the binders (Portland cement and BASS) and mixing of the composite – mortar. The data of emissions and energy usage was compiled from the literature review, theoretical estimations, and information of cement producers. The emphasis was placed on the consideration of local factors, such as composition of energy mix or variety of used materials. Within the analysis, the Czech electricity mix, where the main portion of electricity comes from coal combustion and nuclear power plants, was used [18].

The total amount of emitted CO₂ and consumed energy during manufacturing of 1 m³ of studied composites with 10, 20, and 30% PC replacements with SSA were compared with the data calculated for the reference composite mix. For the intermediate stages, i.e., Portland cement and BASS manufacturing, the obtained values were related to 1 t of a particular product.

4. Results and discussion

Basic structural parameters of studied composites, together with compressive strength data are presented in table 1. The bulk density slightly decreased with increasing dosage of SSA in mortar mix, but differences were mostly in the range of measuring uncertainty. Accordingly, the porosity of mortars with SSA was slightly higher as compared to that measured for control mortar mix. In agreement with structural parameters, mortar compressive strength remained almost unaffected by the SSA incorporation in mortar mix. It was a highly promising finding for the use of thermal treated sewage sludge in concrete and cement-based composited manufacturing.

| Mortar | ρ₀ (kg/m³) | ρₛ (kg/m³) | Ψ (%) | fc (MPa) |
|--------|------------|------------|-------|---------|
| RM     | 2031       | 2251       | 9.8   | 52.4    |
| SSA 10 | 2038       | 2267       | 10.1  | 52.3    |
| SSA 20 | 2004       | 2234       | 10.3  | 51.9    |
| SSA 30 | 2001       | 2235       | 10.5  | 51.8    |

![Figure 1. PC production – outputs and inputs (per 1 t of cement).](image)
The partial life cycle processes included in the LCA analysis are given in figures 1-3. Here, EC stands for energy consumed. In figure 4, environmental impact of SSA use in mortars production is presented. The calculated data showed decreasing trends in both CO₂ production and energy consumption with the increasing dosage of SSA in mortar mix.

**Figure 2.** Sewage sludge processing and SSA production – outputs and inputs (per 1t of SSA).

**Figure 3.** Mortars production – outputs and inputs (per 1m³ of composite).

**Figure 4.** Carbon dioxide and EC for production of 1m³ of composite.
Taking into consideration the functional properties of SSA mortars (table 1), which were close to the control material, the overall benefits of SSA use were quite obvious. The reduction of waste generation with minimization of material landfilling added to the profitability and efficiency of the sewage sludge application as well. The importance of obtained results is underlined by the fact that Czech Republic and Poland belong to major producers of sewage sludge in the EU. Moreover, sewage sludge recycling and reuse is in both countries still very limited.

5. Conclusions

Sewage sludge originating from the municipal wastewater treatment plant was thermally treated. The obtained ash was mechanically activated and used as partial OPC substitute in mortar composition. The positive effect of the use of sewage sludge ash as a partial cement replacement with respect to the energy consumption and GHG emission, considering the compressive strength of the analyzed mortars, was quite apparent. The decrease of energy consumption necessary for the production of the analyzed blended binders was nearly 10% per each 10% of sewage sludge ash used as Portland cement replacement. The energy needed for the sludge thermal treatment at 700°C was 220 MJ/t. The emission of GHG related to the sludge thermal treatment was nearly 40kg/t.

Based on LCA analysis and obtained structural and mechanical parameters of the developed mortars, the presented thermal treatment of sewage sludge and formed SSA can bring both environmental and economic benefits for concrete and cement industry.

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