Cement Substitute in Concrete Manufacturing

Subjects: Construction & Building Technology
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Striving for reduction of production costs and constraints on natural resources cause the use of waste materials as substitutes of traditional raw materials to become increasingly important. Dynamic development of sewerage systems and sewage treatment plants observed over the recent years leads to increase of mass of the produced sewage sludge. According to the Waste Law, the municipal sewage sludge can be used if it is properly stabilized, e.g., through thermal processing. This process results in significant quantities of fly ash which must be properly utilized. The description presents a brief highlight of solution of the abovementioned problem — the possibility of application of fly ash wastes as a cement substitute in the concrete manufacturing. If a predefined quantity of cement is replaced by the fly ash, then one can obtain cement composite with good strength parameters. This assumption is confirmed by the investigations.

Keywords: concrete ; cement ; sewage sludge fly ash ; properties

1. Introduction

Cement—a mineral hydraulic binder, built the modern world; now it turns out that it also destroys it. At the moment, it is irreplaceable; it remains a key material for the construction of the world economy. According to the data of the International Statistics Yearbook [1], the worldwide production of cement in 2000 amounted to over 1.67 billion tons and in 2013—4.07 billion tons. Currently, it is consumed at ca. 4.5 billion tons per year. The problem is that the production of 1 ton of cement, depending on the technology, causes emission of 0.5 to 1 ton of CO_2. It means that the cement production is responsible for 5% of global carbon dioxide emission. The direct source of carbon dioxide emission in the cement industry is the process of raw material calcination (approx. 62%) and fuel combustion (approx. 38%), while the indirect ones are means of transport and electricity production, as well as mining of mineral resources and primary fuels. High CO_2 emission by the cement industry resulted in the development of a strategy to reduce this emission by: improving production processes, modernizing equipment, replacing primary fuels with alternative fuels from waste, optimizing the cement composition, and recovering heat energy from production processes. Striving for reduction of production costs and constraints on natural resources cause that use of waste materials as substitutes of traditional raw materials becomes increasingly important [1][2][3].

2. Development

The dynamic development of sewage networks and municipal sewage treatment plants, visible in the last 20 years, leads to the formation of an increasing amount of municipal sewage sludge. Currently, the method of their management is subject to the Act of 14 December 2012 on waste (Journal of Laws 2013, item 21) [4] as well as executive regulations and laws specific to the way of their generating, processing and impact on the natural environment. Taking into account the ban on the storage of sewage sludge binding from 1 January 2016 [5], their management has become not only a technical and economic problem, but also an ecological one. Until then, the generated sewage sludge was landfilled or, after initial stabilization (aerobic, anaerobic, with lime), was released into the environment, e.g., as fertilizers or for earthworks. However, due to the sanitary hazard, high weight and hydration, they have always been a technical problem. Taking into account the presence of toxic substances and heavy metals, limiting the possibility of their use in agriculture, thermal methods are the most appropriate way of sewage sludge disposal. As a result of this process, the volume of waste (sludge) is reduced and the heat or electric energy is obtained, as well as the content of sulfur and nitrogen compounds in the exhaust gas is reduced. The secondary waste material generated in sewage sludge thermal treatment installations is waste (fly ash) with the code 19 01 14, which also requires appropriate management. Due to their origin, these ashes are characterized by specific properties (high phosphorus content), absent in by-products of coal combustion. In line with the idea of Circular Economy—a near-zero emission economy—ashes from sewage sludge should be treated as a potential product [4].

According to the binding regulations in Poland ([5], pos. 108), implementing the Directive of the European Parliament and Council (EU/2010/75) [6] within their scope, insofar as the ashes produced during the combustion of sewage sludge satisfy defined requirements, they can be used to prepare concrete mixtures for construction purposes, with the exception of buildings intended for the permanent residence of people or animals and for the production or storage of food. Due to the increase in the generated sewage sludge, it became necessary to find alternative methods of their application. One of such methods is utilization in technology of concrete and other building materials based on cement [5][6].

Concrete is currently the most widely used man-made composite material, and second after water, in the entire range of materials used. It is an ecological material, made of local raw materials—aggregate, cement, water, admixtures and mineral additives, with the smallest carbon footprint. The use of secondary raw materials in the production of concrete—fly ash from thermal conversion of sewage sludge (as a partial replacement for cement—a cement substitute) is important not only from the economic but also the environmental point of view. In the environmental aspect, the benefits of using fly ash include, among others:

- limitation of the use of natural deposits, and thus savings in fossil fuels and natural resources and limitation of the devastation of the land surface as a result of the exploration of aggregates;
- reduction of the environmental pollution by reducing the emission of harmful gases (carbon dioxide);
- reduction of the amount of landfilled waste;
- recovery of land occupied by ash dumps.

The research on the fly ash from thermal conversion of sewage sludge (SSA) presented in the literature focuses on determining its potential for application in building materials such as: burnt tiles, bricks [7][8][9], glass ceramics [10][11][12], mortars, cement pastes and concretes [13][14][15][16]. This additive is used as a direct substitute for cement, sand or clay. It is assumed that mixing a certain amount of SSA with other ingredients does not adversely affect the compressive strength of mortars and concretes. Monzo et al. [17] found that mortars matured in water at 40 °C and containing up to 30% SSA did not show a reduction in compressive strength compared to reference mortars without the addition of ash. The changes in mortar strength are related to the pozzolanic properties of the SSA, the content of C_3A in the cement and the maturation conditions. In the studies of Cyr et al. [18], ash was introduced to the mortars in the amount of 25% and 50%. It was estimated that SSA caused a decrease in compressive and bending strength compared to the control mortars. Lin et al. [19] concluded in their research that the fly ash from thermal conversion having a finer graining shows a higher pozzolanic activity, which results in a higher compressive strength of building materials. Chen et al. [20] analyzed the effect of ash as a substitute for cement and sand in concrete. Their tests showed satisfactory compressive strength of the prepared composites. Ing et al. [21] as well as Pinarli and Kaymal [22] confirmed that mortars containing up to 10% SSA have similar or greater compressive strength than conventional mortars. Baeza-Brotons et al. [23] proved a satisfactory strength after 28 days of maturation of concrete containing 5, 10, 15 and 20% of ash. Moreover, they found that the ash influences the water absorption in the cement composite. In the studies of Chang et al. [24], it was confirmed that the fly ash used as an additive to concrete mix in the quantity up to 10% has a positive effect on compressive strength. In addition, this additive also affects the water absorption capacity of the material. Chen and Poon [25] proved in their studies that the pozzolanic effect of SSA is weaker than that of powdered fly ash (PFA). However, at the same exchange level of up to 20% of cement, the compressive and bending strength of the mortars are comparable. The optimal content of the fly ash from thermal conversion of sewage sludge in cement composites, according to the information provided by other authors, is within 5–20% [26][27][28][29][30][31][32][33][34]. Pozzolanic properties and chemical composition of the fly ash from thermal conversion of sewage sludge used as a substitute of cement in concrete show analogy to traditional mineral additives [35].

3. Conclusions

From the ecological point of view, the reuse of waste—fly ash with the code 19 01 14—brings great economic benefits. Proper disposal and thermal treatment allows for its reuse. The investigations [1] proved that it is possible to use the fly ash from thermal conversion of sewage sludge for the production of concrete as a partial substitute for cement. The obtained results and their analysis allow for the following conclusions:

- The generated waste—the fly ash from thermal conversion of sewage sludge used for the production of concrete positively affects its compressive strength and frost resistance.

- The concrete containing the fly ash from incineration of sewage sludge in its composition presented a compressive strength comparable to that of the reference concrete without additives. The ash can be used as a cement substitute if its content does not exceed 20%.
- There is no typical composition and quality of municipal wastewater, and thus there is no typical composition of fly ash generated during thermal conversion of sewage sludge.
- The fly ash from thermal conversion of sewage sludge has a different physicochemical composition compared to the silica fly ash used in concrete technology and does not meet the requirements of PN-EN 450-1: 2012. The oxides of silicon, calcium, phosphorus and aluminum had the largest share in the composition of the ash samples.
- Concretes made with ash in the amount of 5%–25% are frost-resistant. The concrete containing ash from sewage sludge obtains satisfactory strength parameters after 150 freezing and thawing cycles.
- The action of high temperature damages the structure of the tested concrete, and visible scratches and cracks appear on its surface.

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