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Use of fly ashes from municipal sewage sludge combustion in production of ash concretes

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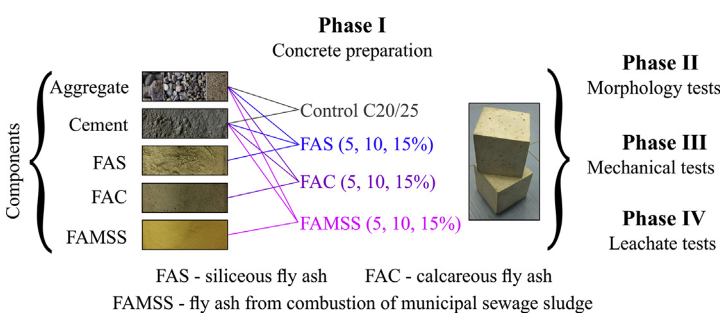
HIGHLIGHTS

- Combustion fly ashes of municipal sewage sludge party replacing cement.
- Impact of municipal sewage sludge on the strength and frost resistance of concrete.
- The results compared with those of concrete containing siliceous and calcareous fly ashes.
- Assessment of heavy metals leachability.

GRAPHICAL ABSTRACT



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ABSTRACT

Application of fly ashes from combustion of municipal sewage sludge (FAMSS) in the concrete technology realizes assumptions concerning the European Union's waste management proposal. This study investigates the influence that a partial replacement of the Portland cement by these ashes would exercise on the strength parameters of concrete if compared to a reference concrete and concretes containing conventional admixtures in their composition, such as siliceous and calcareous fly ashes. Potential environmental impact of FAMSS application was investigated through the determination of heavy metals leachability. Results conveyed that the concretes containing fly ashes from combustion of municipal sewage sludge improved strength parameters and frost resistance as well as satisfied the environmental requirements imposed on leaching of heavy metals.

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1. Introduction

The idea to apply fly ashes in production of ordinary concrete is not new. Originally, it was used in the USA in 1930s [1–4]. Various sorts of coal and technologies related to its combustion or co-combustion recall formation of various fly ashes, like siliceous, silica-calcareous or calcareous ashes. The combustion by-products in the professional power industry were disposed on the earth's surface or in underground mines [5]. In Europe, siliceous fly ashes produced in the combustion of hard coal are widely applied in the cement technology and even more so in concrete technology. The re-use of this material allows the use of reduced quantities of cement clinker, natural raw materials and mineral fuels as well as the reduction of environmental pollution and emission of carbon dioxide [6–8]. The clinker production process is associated with high emission of carbon dioxide (1 kg CO_2 per 1 kg of produced clinker) as well as with high energy consumption needed for clinker roasting at the temperature of 1450 °C [9]. The carbon dioxide emission limits, imposed by the European Union [10], prompt research on materials of new generation, containing lower quantities of clinker.

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Wide application of fly ashes from coal combustion in the building construction is chiefly a result of: high fineness, close to that of cement; chemical constitution and phase composition; and reactivity, in particular pozzolanic activity. Simultaneously, the fly ashes have a positive effect on some features of concrete, like compressive and bending strength [11–13]. These factors cause the production of ash concretes to be attractive both for producers and for final consumers [14,15]. Concrete production in the EU in 2015 amounted to $266.9 \cdot 10^6$ m^3. To produce such quantities of concrete, $128.1 \cdot 10^6$ tons of cement and $7.86 \cdot 10^6$ tons of admixtures were used. The most popular concrete was of class C25/30 – C30/37 (55.4%) and of thick-plastic (S2) to semi-liquid (S4) consistency – 74%. [16].

In recent years, many investigations have been conducted focusing on possibilities of application of fly ashes from combustion of municipal sewage sludge (FAMSS) in the concrete technology [17–20]. Neutralization and recycling of sewage sludge, formed in sewage treatment plants, is a serious ecological problem. The legal, binding regulations in Poland legislate the problem of the sewage sludge disposal on overfilled landfills more and more severely and have introduced a ban on the disposal of wastes characterized by high calorific value, exceeding 6 MJ per one kilogram of dry mass [21]. Hence it seems that a target direction of the neutralization of sewage sludge in Poland is determined mainly by thermal methods of neutralization, considered to be ecologically safe and economically justified [22,23]. Despite a significant reduction in volume, up to 90%, of municipal sewage sludge, these methods have not yet been commonly applied to combustion of other wastes [24–27]. One of possibilities of recycling the formed ashes is their use in the production of building materials, such as ordinary concrete [28], which generally increases the waste recycling – a more environmental friendly option of waste treatment than disposal [25,29].

However, there are no implementations using ashes formed during sewage sludge combustion. The mass of sewage sludge produced per annum in the 28 European member states decreased from approximately 8.5 Mt dry mass in 2012 to 3.5 Mt dry mass in 2015 [30]. According to the data of the Eurostat [30], the percentage of thermally conversed sewage sludge in EU took values of 25% and 37%, respectively. Application of this method of sewage sludge disposal results in the production of significant quantities of fly ashes, classified as waste code 19 01 14 [31], which should be appropriately recycled. According to the regulations binding in Poland [32], implementing the directive of the European Council [33] within their scope, insofar as the ashes produced during the combustion of sewage sludge satisfies defined requirements, they can be used to prepare concrete mixes for building construction, excluding buildings designated for permanent residence of humans or animals as well as for food production or storage. Recent experimental studies suggest that the application of ashes from municipal sewage sludge combustion allows the obtaining of concrete parameters comparable to those for concrete produced on the basis of fly ashes from combustion or co-combustion of coal [34–36,27].

Standards and directives concerning the application of ashes from thermally conversed municipal sewage sludge as a mineral raw material for production of building materials (concrete) on the basis of cement have not been worked out so far. Due to a small number of studies and practical applications using such ashes, further information on possibilities of their application is essential. The main objective of the performed investigations was the assessment of possibilities of re-using ashes from municipal sewage sludge combustion, based on a comparative analysis of properties of a concrete mix and hardened concrete containing FAMSS as well as siliceous and calcareous fly ashes, currently widely used in the concrete production. The obtained results were compared to the sample, not containing any fly ashes in its composition.

2. Materials and methods

2.1. Characteristics of fly ashes from municipal sewage sludge combustion

The test procedures were based on the directives contained in the binding regulations and EU standards. The investigations of FAMSS were carried out to identify their physical and chemical properties as this material is not currently widely used in the cement production.

The grain size distribution analysis was carried out on the base of a laser diffraction phenomenon in deionized water and in the presence of an ultrasonic probe, using the Mastersizer 3000 analyzer (Malvern Instruments). Grains with equivalent diameters from the range $0.1 \div 1000\ \mu m$ were analyzed. The morphology and chemical composition were determined with use of the scanning electron microscope SEM Quanta 250 FEG (FEI), equipped with an Energy Dispersive X-Ray Spectroscopy (EDAX).

The oxide composition of the investigated fly ash was established with the method of energy dispersive X-ray fluorescence (XRF) on the Epsilon-3 spectrometer (Panalytical) with the Rh X-ray tube (9 W, 50 kV, 1 mA), 4096-channel spectrum analyzer, 6 measuring filters (Cu-500, Cu-300, Ti, Al-50, Al-200, Ag) and the high-resolution solid state SDD detector (50 µm thick beryllium window), cooled with a Peltier's cell. Powdered X-ray diffraction (XRD) test was carried out using a Panalytical X'pertPRO MPD X-ray diffractometer with the PW 3020 goniometer. As an X-ray radiation source, the copper tube was used (CuK_α radiation, $\lambda = 1.54178$ Å). The data handling was performed with the help of the X'Pert Highscore software. The identification of mineral phases was based on the PDF-2 Release 2010 database, formalized by JCPDS-ICDD.

2.2. Preparation of concrete specimens

The investigated concrete samples were designed as an ordinary concrete according to European standards [37]. To perform the tests, concrete mixes of class C20/25 and thick-plastic consistency F2 were designed. Constant granulometric composition of fine aggregates, selected in a sieve analysis, as well as of coarse aggregates, selected by consecutive iterations (Table 1), were maintained in all samples. Composition of the mix was designed using the method of three equations by Bukowski [38]. To prepare the concrete samples, a natural aggregate was used with graining $0.125 \div 16$ mm, the CEM I 32.5 Portland cement as well as admixtures. As the mineral admixtures for the concrete mix, fly ashes from the fluidal combustion of municipal sewage sludge in the "Czajka" sewage treatment plant (Warsaw) were used. The combustion was carried out in spring, in temperatures above 850 °C. As reference materials, conventional siliceous fly ashes from hard coal combustion in the "Siekierki" power plant (Warsaw) as well as calcareous fly ashes from brown coal combustion in the "Bełchatów" power plant were used. The temperature of coal combustion in the power plants did not exceed 550 °C. The fly ashes from the coal co-combustion met the requirements given by European standards [39]. To compare features of traditionally produced ordinary concretes and features of the concretes containing combustion by-products in form of fly ashes – siliceous and calcareous ones as well as ones formed in thermal conversion of municipal sewage sludge – four types of concrete samples were prepared:

1. Concrete without admixtures – CON,
2. Siliceous fly ash admixtured concrete – FAS,
3. Calcareous fly ash admixtured concrete – FAC,
4. Concrete admixtured with fly ashes from combustion of municipal sewage sludge – FAMSS.

In the individual samples admixtured with fly ashes, 5%, 10% or 15% of a defined cement mass was replaced by the ashes. The concrete mix recipe per 1 m^3 was established to comply with the assumption of ordinary concrete mix with use of the method of three equations. Proportions of the concrete mix tested in the study are shown in Table 2. After forming, the samples were cured by immersion in tap water at 18 ± 2 °C [37].

2.3. Characteristics of concrete

In order to characterize properties of the obtained concrete mixes, the following tests were performed: bulk density test (measurements of mass and volume), [40] consistency test (concrete slump test) [41] and air content test (pressure method) [42]. The compressive strength tests were performed according to the guidelines contained in European standards [43]. The samples were tested after 28 and 56 days of curing. The frost resistance test was performed with use of the direct method [44]. All tests were performed on the samples of the size 150 × 150 × 150 mm. The compressive strength tests were performed in the H011 Matest hydraulic test machine, and the frost resistance tests in the Toropol cold chamber.

The leaching tests were performed for three analysed fly ashes and for the concrete sample without admixtures (CON). In addition, the tests were performed for three concrete samples admixtured with fly ashes where 15% of the cement mass was replaced by individual types of fly ashes. The tests were performed for the samples with the highest percentage of fly ashes because it had been assumed that the

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