Original Research

Application of SSA as Partial Replacement of Aggregate in Concrete

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Abstract

One current method of sludge disposal is incineration. Although incineration reduces the volume of sludge, it is not a final solution since it generates ash that must subsequently be disposed of. This study assesses the feasibility of utilizing the ash derived from sewage sludge incineration (SSA) as a component of concrete. Considering the chemical and physical properties of sewage sludge ash, an attempt was made to introduce it into concrete as a partial replacement of natural aggregate. The untreated ash was used as lightweight aggregate. Properties of innovative material derived from sludge and its suitability for concrete technology were discussed. It was found that the waste aggregate strongly influenced mechanical and physical properties of concrete, but the strength characteristics required for structural concrete could be reached.

Keywords: sewage sludge ash, concrete, lightweight aggregate, strength development

Introduction

Municipal sewage treatment results in the formation of nuisance waste in the form of sewage sludge. Despite the introduction of high-performance methods of consolidation, stabilization, and dewatering of sludge in most sewage-treatment plants, the problem of further disposal (recycling and reusing) still exists. Nowadays the use of landfills is the dominant manner of sludge disposal, but it is a temporary solution while considering domestic and European Union legal standards. The utilization of sludge for agriculture (as fertilizers) has become more and more difficult after the introduction of increased regulations concerning the use of fertilizers and their standardized quality. The incineration of sludge seems to be an interesting and acceptable solution [1, 2]. The incineration of sewage sludge is a common technique that allows conversion of bulky sludge into practically inert, odorless ash. The conduction of drying and incineration of sewage sludge demands complying with numerous technical and legal conditions.

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The process of sludge incineration begins when the dewatered sludge, containing 15-25% dry solids, is introduced into the drying chamber. After drying, the sludge containing 75-95% dry solids is introduced to a furnace, where the proper process of incineration takes place. The desiccated sludge is fuel of relatively high heating value. The drying system is used in conjunction with a waste-to-energy furnace for sludge incineration. The incineration plant is also equipped with a system for exhaust gas cleaning. The products of incineration are slag, ash, and exhaust gas. Because of the connection between the thermal drying treatment and combustion of sludge, with the gas cleaning the system becomes not only environmentally friendly, but also the sludge is disposed of in an economical manner [2, 3].

The development of technology in different industrial sectors has caused the formation of new kinds of by-products or significant changes in composition and properties of known waste. Knowledge about them is usually insufficient among potential consumers. As yet, there is no sufficient background knowledge for the utilization of different ashes from the combustion of sludge as a component in concrete manufacturing, either from an environmental point of view

Table 1. Composition of concrete mixes in kg/m^3 and selected properties of hardened concrete.

Component	Content of waste aggregate in concrete mix [%]				
	0%	10%	25%	50%	100%
Cement [kg]	300	300	300	300	300
Water [kg]	150	150	150	170	200
Sand 0/2 [kg]	798	718	599	399	0
Natural aggregate 2/4 [kg]	499	449	374	250	0
Natural aggregate 4/8 [kg]	699	699	699	699	699
Waste aggregate dosage by volume	0	0.10 V_k	0.25 V_k	0.50 V_k	1.0 V_k
Waste aggregate [kg]	-	73	182. 5	365	730
Physical properties of hardened concrete					
Bulk density [kg/m^3]	2277	2216	2179	1900	1652
Water absorption [%]	4.43	4.73	5.37	8.72	14.87

V_k – total volume of sand (0/2 mm) and 2/4 mm aggregate.

or from a technical standpoint. The evaluation of waste material suitability for each application should take the following factors into account: suitability for processing, the influence on technical characteristics of the material, and environmental impact.

Attempts at multidirectional economical use of ashes from the combustion of different fuels have been made for years [4-6]. One of their main users is the industry of building materials. The method of building material manufacturing makes it possible to dispose of large amounts of waste from other industrial sectors. Many incineration residues have been successfully used in construction materials [4, 7, 8]. Sewage sludge, especially after thermal processing, can also be utilized in this manner. The amount of waste suitable for disposal and the requirements for them depend on the type of building material produced.

At present, the most widely applied treatment for the inertization of ash from municipal waste is the solidification/stabilization process, generally using cement as a binder [4, 9, 10]. The standard for concrete EN 206-1: 2003 [11] allows the introduction of different mineral additions that can influence the features of fresh concrete as well as the properties of hardened concrete. Two types of inorganic additions are mentioned:

- almost neutral (type I) – substances inert in the environment of hydrating cement,
- additions with pozzolanic properties or latent hydraulic properties (type II) – substances active in the environment of cement paste.

The research study conducted to examine the potential for utilizing ground sludge ash as a partial replacement for cement in concrete (active addition, type II) was reported in [12].

The present study concerns the use of sewage sludge ash as an aggregate in concrete. Although the ash could eventually be used as an addition to the finer fraction of sand, a more promising use is in lightweight concrete as a substitute of commercially available lightweight aggregates. The production of artificial lightweight aggregate from sludge has been investigated by various researchers [13-15]. In previous studies the sludge ash needed some special treatment (pulverizing, sintering, vitrification, etc.) for aggregate manufacturing. The ash from sludge incineration in a considered wastewater treatment plant is a fine granular waste material, potentially attractive as a filler in concrete.

Taking into account the character of material tested, its chemical composition, particle size and structure, an attempt was made to introduce it to concrete in an untreated form as a replacement of natural aggregate – neutral addition (type I).

Requirements for the application of ash originating from the combustion of sludge, as components of concrete, are not standardized, thus the investigations were carried out using the methods for aggregate and mineral additions for concrete.

Materials and Methods

The ash tested was obtained as a result of the incineration of sludge from a municipal wastewater treatment plant. The process includes two stages. At first, the sludge with moisture content of 80% is dried using recirculated air at 50ºC. In the thermal treatment system the dried sludge with moisture content of 20% is incinerated in the furnace chamber, in bottom section at a temperature above 600ºC, and later in the upper section, the sludge is subjected to more than 850ºC. The residence time of the combustion gas molecule in the afterburning chamber is longer than 2 seconds. The composition of cleaned gas, emitted to the atmosphere, is monitored continuously.

The characterization of sludge ash was performed to investigate the potential of exploiting these residues as a filler in concrete (neutral addition). The sludge ash characteristics were determined including the chemical composition, bulk density, specific gravity, particle distribution, and water absorption.

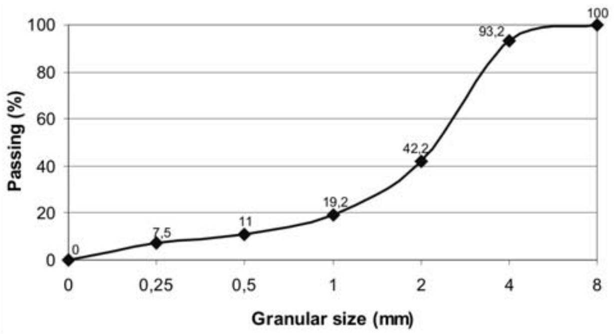

Fig. 1. Average grain size distribution of ash in natural untreated state.

The analysis of the ash morphology was carried out by means of a scanning electronic microscope (E-SEM), which allows the observation of samples without their coating with electric current conductible material and without the necessity of high vacuum in a specimen chamber. The preliminary analysis of chemical composition of ash particles was conducted by an energy-dispersive X-ray analyzer EDS.

A characteristic feature of lightweight aggregates is the porous structure and, as a result – considerable water absorption. The high absorption of lightweight aggregate can cause difficulties in concrete performance, particularly in the weight-dosage of components. Changes in water content in fresh concrete must be taken into account in concrete mix compositions.

The specimens tested were prepared using Portland cement CEM I 42,5N – HSR/NA and natural aggregate of 8 mm was used. The natural aggregate mix consisted of 40% of 0/2 mm fraction, 25% of 2/4 mm fraction, and 35% of 4/8 mm fraction.

The SSA was introduced into concrete in the form received from the producer, without any special treatment, to evaluate the possibility of its direct utilization.

The compositions of all concrete mixes are presented in Table 1. The ash was used as the lightweight aggregate replacing the part of aggregate of size from 0 to 4 mm in concrete. The total volume of 0/2 mm and 2/4 mm aggregate was called V_k in Table 1. The concretes tested contained 0%, 10%, 25%, 50%, or 100% of ash replacement related to aggregate volume. The natural aggregate of 4/8

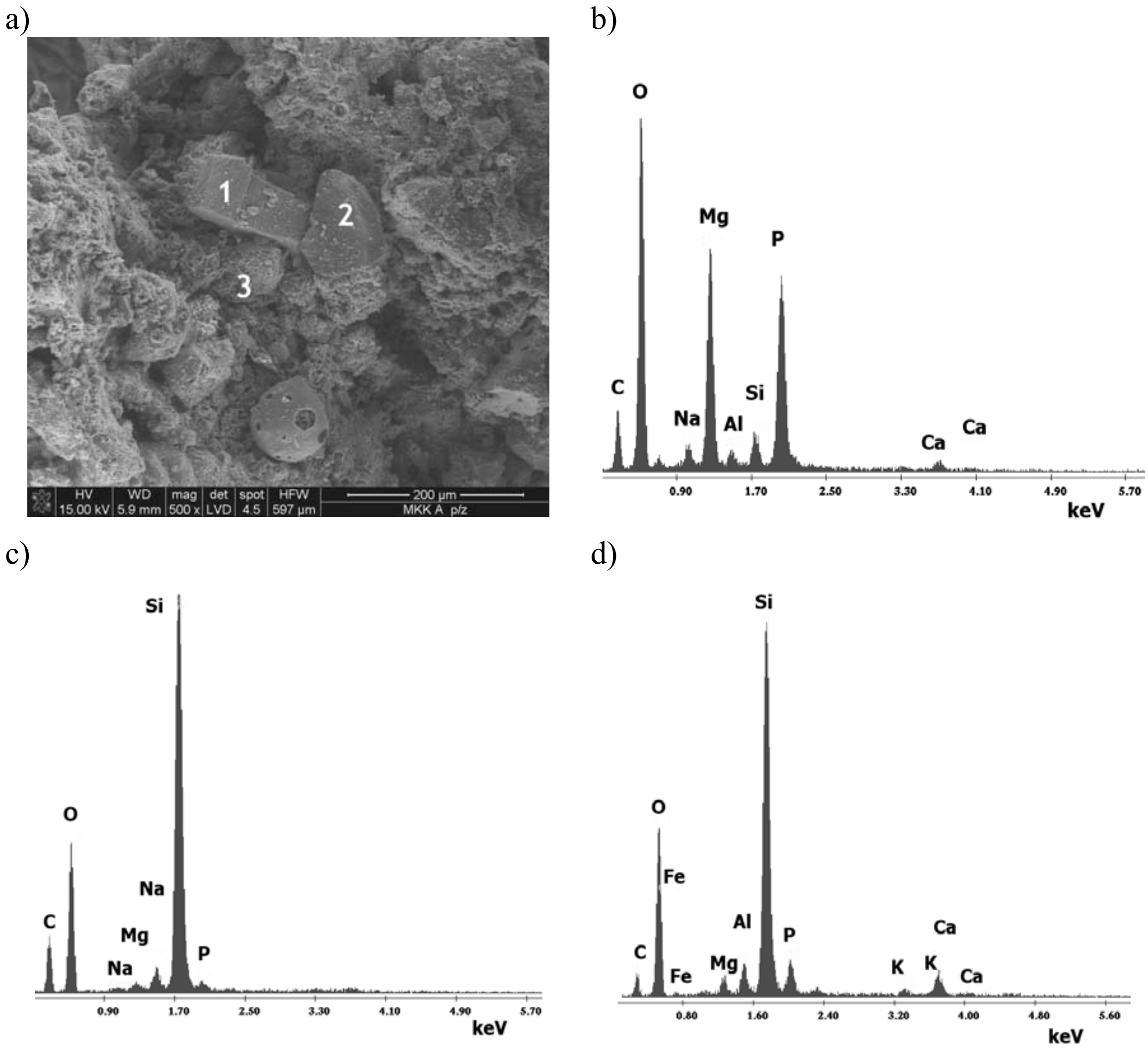

Fig. 2. E-SEM micrograph of sewage sludge ash. 500× (a) and EDS analysis in selected points: EDS in point 1 (b), EDS in point 2 (c), and EDS in point 3 (d).

Table 2. Chemical analysis of ash tested.

Component	Average content
Loss on ignition (%)	8.65
SiO_2 (%)	34.68
Fe_2O_3 (%)	10.32
Al_2O_3 (%)	6.32
CaO (%)	15.42
MgO (%)	2.65
TiO_2 (%)	0.41
SO_3 (%)	0.60
S^{2-} (%)	0.20
Na_2O (%)	0.70
K_2O (%)	1.30
Cl^- (%)	0.02
P_2O_5 (%)	18.17
Trace elements	
Cr (ppm)	85
Cd (ppm)	<0.375
Zn (ppm)	1119
Cu (ppm)	357
Ni (ppm)	65
Pb (ppm)	26
Hg (ppm)	0.20

mm fraction was used in all concrete mixtures. The porous, water-absorbing SSA aggregate had an effect on concrete workability. Thus, the content of water in mix containing 50% (0.50 V_k) and 100% (1.0 V_k) of waste aggregate had to be increased to achieve suitable workability.

The fundamental technical characteristics of cement-based composites, determining their practical applications, are mechanical properties (particularly compressive as well as flexural strength). The research programme included the estimation of the influence of ash from sludge combustion as a partial replacement of aggregate on mechanical properties of concrete and also on other applicable characteristics such as water absorption and bulk density.

The tests of physical properties and strength of concrete were conducted using prism-shaped specimens (40×40×160 mm). After forming, the specimens were cured by immersion in tap water at 18±2ºC.

The strength tests were performed at the age of 28, 90, and 180 days [11]. The flexural strength was determined on the prism-shaped specimens in bending test and every series consisted of three replicates. The compressive strength was determined on half-prism specimens and every series consisted of six replicates.

Results and Discussion

The Characterization of Ash Used

Burnt sludge has the form of mix of bottom ash and slag with bulk density of 500 kg/m^3 and specific gravity 2,520 kg/m^3. The grain size distribution of ash in natural state is presented in Fig. 1. The particle size of ash does not exceed 4 mm. The content of finer particles, i.e. the grains of diameter smaller than 0.25 mm, is approximately 7%. Therefore, the material can be classified as fine lightweight aggregate for use in concrete, to which aggregate of density less than 1,800 kg/m^3 belongs, according to EN-206-1: 2003 [11].

Selected results of the microstructure observation and qualitative analysis are shown in Fig. 2. The ash exhibited loose and rough structure. The irregular particles with strongly extended surface dominated in the material. Spherical and similar to rectangular forms of grains were very rare. In chemical composition the presence of such elements as silicon, carbon, magnesium, aluminium, iron, calcium, and phosphorus were identified. The detailed chemical composition of ash, considering the trace elements content, is presented in Table 2.

Silica, iron, and calcium oxides are the major compounds of ash. The ash was characterized by relatively low content of aluminium oxide and a low sulfur trioxide level. The unburnt carbon, expressed by the loss on ignition, and the significant content of phosphorus pentoxide can influence the strength development dynamics [2]. No extreme values of trace elements content were observed. The water extract from ash was characterized by average pH value of about 8.6. The average water absorbability of ash in natural state was 65% after 24 h and 71% after 48 h of test.

Properties of Concrete with Sludge Ash Aggregate

The specimens with up to 25% replacement of natural aggregate by waste aggregate showed totally different properties in comparison to these containing 50% or 100% of lightweight filler.

The results of bulk density and water absorption tests for concretes containing lightweight aggregate are summarized in Table 1. On the basis of bulk density results presented in Table 1, it was found that the addition of the lightweight aggregate caused a decrease in concrete density, proportionally to the content of waste aggregate in total aggregate composition. Water absorption of concrete increases together with the increase in SSA content, but concretes containing 10% or 25% of lightweight aggregate show the absorption 4.73% and 5.37% comparable with that of ordinary concrete equal to 4.43%. Concretes with 50% and 100% of sludge ash cannot be exposed to weather conditions because of high water absorption, equal to 8.72% and 14.87%, respectively.

The variation in compressive strength with curing time of concretes is presented in Fig. 3. The results observed prove the significant influence of waste aggregate on strength development at all ages. The graphs show that the rate of strength development of concrete with ash is comparable to that of the control concrete, but the strength values obtained are strongly dependent on waste aggregate content in concrete. For concrete containing 50% and 100% of waste aggregate, tested after 28, 90, and 180 days of storage, a significant decrease (from 60% to 75%) in compressive strength was observed in comparison to the control concrete. The tests carried out for concrete with lower content of the lightweight aggregate, i.e. 10% and 25% in relation to the natural aggregate, brought the following results: after 28 days the strength of concrete containing 10% or 25% of addition was comparable to compressive strength of the concrete with natural aggregate, and after 90 and 180 days of the strength of concrete with up to 25% aggregate, replacement even exceeded the control concrete strength. The reason for this finding is in the chemical composition of SSA (Table 2), different from typical composition of natural aggregate (inert filler). The chemical composition and the finess of material are responsible for pozzolanic activity of ash. The pozzolana is material containing active silica which in fine-grained form and in the presence of water reacts chemically with the lime hydrate at normal temperatures, forming stable compounds characterized by hydraulic properties, analogous to the compounds being formed during Portland cement setting [16]. Probably, the pozzolanic properties of fine particles of SSA described in [12] have beneficial influence on strength development after prolonged curing time [16]. This effect can be observed for concrete containing up to 25% of aggregate. For greater content of waste aggregate (50% and 100%), low strength of lightweight aggregate determines the relatively low strength of concrete.

Although concrete mechanical properties are worsened by waste addition, the minimum compressive strength (30 MPa), required for structural concrete is reached by selected concrete mixtures after 28 days. The use of ash filler in more than 50% of aggregate volume should be limited to concrete with compressive strength not greater than 15 MPa.

The analysis of the flexural strength test results (Fig. 4) after 28 days pointed out that the replacement of 50% or 100% of fine aggregate by waste material gives strength values almost three times lower in comparison to concrete with natural aggregate. Better results were observed for concrete containing up to 25% of waste aggregate just after 28 days of curing, meaning that for 10% volume replacement of fine aggregate the decrease in flexural strength was approximately 20%, and for the 25% content of light filler the strength dropped approximately 26%.

After 90 and 180 days, the flexural strength of concrete with up to 25% of waste aggregate attained strength similar to control concrete strength. As shown in Fig. 4, the difference in flexural strength between lightweight concrete containing no more than 25% of SSA and control concrete was about 0.5 MPa.

The leaching test was carried out on concrete with 25% of SSA aggregate. The leaching level of heavy metals was negligible, significantly below the limits for inert waste,

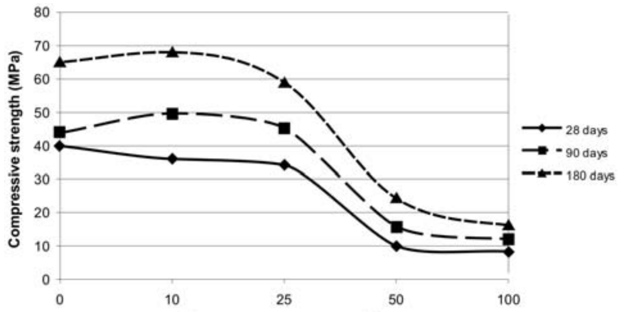

Fig. 3. Compressive strength development of concrete containing waste lightweight aggregate.

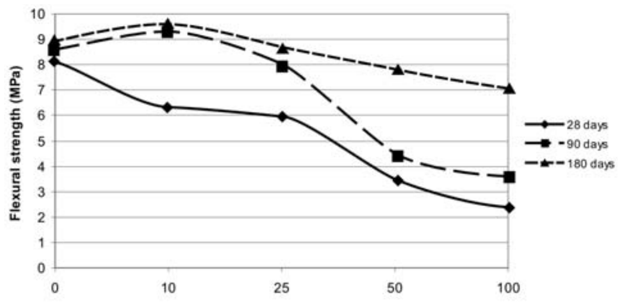

Fig. 4. Flexural strength development of concrete containing waste lightweight aggregate.

acceptable for introducing it into the water or soil. The small content of heavy metals released from the concrete could be explained by immobilizing properties of cement composites, thanks to which they are permanently bound by calcium silicate hydrate (CSH phase) and calcium aluminate hydrate being formed during the hydration process [3, 9]. The use of SSA in concrete does not pose any environmental risk.

Conclusions

Future trends in sludge management go toward its reutilization as a useful resource. The disposal problems will be drastically reduced if sludge ash can be put to large-scale economic applications. The waste disposal in concrete technology prevents devastation of the environment, because it limits natural resource consumption as well as diminishing the amount of waste deposited on landfills. The granular ash from incineration of sewage sludge is valuable material that can be reused in a natural untreated state in concrete as a partial substitute of lightweight aggregate. The use as an aggregate is the least energy consuming option for waste disposal. The SSA strongly influenced technical properties of concrete. The acceptable replacement level for structural applications is up to 25% of natural aggregate volume, provided compressive strength, density, and water absorption values adequate for service conditions of concrete structure.

The test results showed that mixes with up to 25% of sludge ash were able to develop acceptable compressive strength and water absorption. Although the SSA was used as a filler, the latent pozzolanic activity of ash allows developing the concrete strength properties comparable with the strength of concrete containing natural aggregate only. The product can also be suitable for non-structural applications where the high strength is not needed and the dosage of waste aggregate can exceed 25% of aggregate volume.

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