Sewage Sludge Bottom Ash Characteristics and Potential Application in Road Embankment

Katarzyna Zabielska-Adamska (ID)

Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology,
15-351 Bialystok, Poland; kadamska@pb.edu.pl

check for updates

Abstract: The paper focuses on sustainability-related applications in civil engineering by using environmentally friendly, alternative construction materials. The paper presents geotechnical properties of thermally converted, municipal sewage sludge in a grate furnace in an incineration plant. Bottom ash and its mixture with sand have been tested to show that they can be considered as a substitute for natural soil built-in road embankments. The product of sewage sludge combustion and its combination with sand meet all code requirements for material suitable for road embankments. As a result of the 30% reduction of resistance to failure values after waste soaking, which causes relatively low California Bearing Ratio (CBR) values of soaked waste, waste should be built into places isolated from groundwater and precipitation. That is also indicated by the possibility of heavy metals leaching from the waste because such content is much higher than in uncontaminated soils, although leaching does not exceed the limits commonly quoted for natural soil solutions. Tested bottom ash as a product of combustion in a grate furnace is a more preferred material for earthworks than fly ash generated during incineration in a furnace with fluidized bed due to the particle size and heavy metal concentrations.

Keywords: sewage sludge ash; bottom ash; earthworks; requirements for waste material; embankments

1. Introduction

Incineration of sewage sludge from urban wastewater treatment plants raises considerable controversy because of emissions of nitrogen oxides, heavy metals, and other harmful substances, forcing costly investment for the purification of exhaust gas, which, in turn, generates hazardous air pollution control residues [1–4]. However, in many countries the increase in the amount of sludge being converted by thermal processing has become one of the fundamental objectives in municipal sewage sludge management systems. Implementation of the objective requires an increase in the municipal sewage sludge mass combustion in mono-incineration technologies or co-combustion in coal power plants and in cement kilns. Table 1 shows sewage sludge production and disposal in given European Union countries in 2016 and 2017 based on Eurostat [5].

In Poland, 30 June 2010, there were only three municipal sewage sludge incineration plants with a total capacity 37,300 Mg/year. In the near future, installations for drying and thermal treatment of sewage sludge are planned to be launched, which will be able to utilize a total of 189,000 Mg d.s./year of municipal sewage sludge [6]. For comparison, as early as the beginning of the twenty-first century, in European countries such as the Netherlands, Austria, Belgium, and Germany, incineration accounted for a significant proportion of sewage sludge management, exceeding half of the total amount of deposits. In the United States and Japan, combustion reached, respectively, 25% and 55% of the total amount of sludge at the end of the twentieth century [1].

Although incineration decreases the volume of municipal sewage sludge, it produces new waste that must be disposed of. The use of this waste as a material for engineering structure is a way to a

employ a circular economy and brings benefits, inter alia, a reduction in the cost of the treatment of sludge and avoid the transfer of waste to landfill [7]; however, the waste must be assessed according to standardized procedures [8]. In the majority of plants, the sludge is incinerated in fluidized bed furnaces in the temperature range of 850–950 °C. The residue after such thermal transformation is mainly fly ash captured from the flue gas in electrostatic precipitators. In the case of the fluidized bed furnaces, almost all of the ash can be removed from the bed and carried away by the flue gas [1]. There have been satisfactory attempts to exploit the sewage sludge ash (SSA) reported worldwide. Most studies concern the application of the SSA as a fractional substitute for cement or aggregate for concrete [9–13] or soil stabilization [14]. Geoengineering studies were carried out on the use of by-product to stabilize soft subsoil of cohesive soils in a 4:1 ratio with cement or hydrated lime [15,16]. Sintered or vitrified SSA can also be used as an aggregate [17,18].

Table 1. Sewage sludge production and disposal in the selected countries of the European Union in 2017 and 2016 according to Eurostat [5], in Mg 10^3 d.s.

Country	Sludge Production—Total	Sludge Disposal—Total	Sludge Disposal			
			Agricultural Use	Compost and Other	Landfill	Incineration
Austria *	238.0	238.0	48.3	47.9	0.1	127.3
Belgium	–	151.7	30.6	–	0	120.7
Czechia	223.3	223.3	102.9	73.1	22.3	25.0
Estonia *	18.3	18.3	0.1	15.4	2.8	–
France	1184.0	809.0	299.0	318.0	13.0	149.0
Germany *	1794.4	1773.2	423.5	200.5	0	1142.9
Greece *	119.8	119.8	21.5	–	34.0	38.4
Hungary	264.7	232.1	28.2	138.4	1.3	64.2
Ireland	58.8	58.8	46.5	10.1	0.1	0
Lithuania	42.5	40.9	20.8	16.7	3.2	0.2
Netherlands *	347.6	325.1	0	4.2	1.1	319.9
Poland	584.4	584.4	108.5	25.9	15.3	106.2
Portugal	119.17	–	13.9	–	5.1	–
Slovakia	54.5	54.5	0	24.6	7.9	12.2
Spain **	1082.7	1082.7	754.7	–	150.9	39.7
Sweden *	204.3	191.4	69.5	55.6	3.1	4.2
UK **	1136.7	1078.4	844.4	–	4.7	228.9

d.s.—in dry substance, * data for 2016, ** data for 2012, "−" no data available.

It is generally concluded that sewage sludge ash from fluidized bed furnace incineration is classified as insufficient for embankments and road granular sub-bases because of the high value of the liquid limit and the small particle size. Its plastic properties and low sand equivalent would probably cause many inconveniences in their use as a filler in road works [19]. Nevertheless, the SSA may be used as a filler in bituminous mixes with better results than reported for mixes with limestone filler and, similarly, for other active fillers [20]. According to Dhir et al. [21] engineering properties of SSA are not sufficiently presented in the literature. However, studies have mentioned the full-scale geotechnical application undertaken in the United States, using SSA as a landfill cover material, but no details on the performance have been provided. In Japan, around 22,000 tons of SSA was reused for earth and road levelling and reclaimed land covering.

The aim of the study is to present geotechnical properties of sewage sludge bottom ash, henceforth referred to as SSA, thermally converted in the incineration plant in Łomża, Poland, and demonstrate that it can be considered as a substitute for mineral soils. Waste from incinerators in Łomża is a bottom ash, resulting from the combustion of sludge in a grate furnace at a lower temperature than in a fluidized bed furnace. It should be emphasized that a major component of sustainability-related applications in civil engineering should be focused on alternative construction materials by using environmentally friendly materials, concentrating on the use of recycled waste materials [22].

Municipal sewage sludge combustion facility in Łomża was launched in December 2007, as the third incinerator in Poland [23]. The incinerator uses combustion technology based on the combined mechanical moving grate furnace and fluidized bed, with recovering combustion heat used for drying sludge. Incineration in the combustion chamber takes place at a temperature higher than 600 °C,

and afterburning in the top part occurs at a temperature above 850 °C. Installation of a low-capacity incinerator of 7000 Mg d.s./year was designed as mono-incineration technology, but to reduce the operating costs, it was decided that, before incineration, the sludge should be mixed with 23% addition of biomass in the form of wood sawdust from deciduous trees, being a by-product from sawmills. This type of furnace, but with greater capacity, appears to be the most used for co-firing of sewage sludge with municipal solid wastes, for example, in Japan and Germany [1].

2. Materials and Methods

2.1. Characteristics of the Chemical and Mineral Composition of Sewage Sludge Bottom Ash (SSA)

The basic chemical composition of the sewage sludge bottom ash from the combustion of sewage sludge in grate furnace does not deviate from the average values for sludge incinerated in fluidized bed combustors (Table 2). Sewage sludge bottom ash is mainly composed of silicon, calcium, iron, phosphorus, and aluminum. In comparison with coal combustion wastes, sewage sludge bottom ash is similar to coal bottom ash, with a higher content of phosphorus and loss on ignition [23]. SSA of high-calcium content can be characterized by the pozzolanic properties triggered by hydraulic binders [15,16].

Table 2. Basic compounds in Sewage Sludge Bottom Ash (SSA).

Content (%)	Grate Furnace in Łomża [1]	Fluidized Bed Furnaces [2]
Si as SiO_2	37.48	14.4–65.0–(36.1)
Al as Al_2O_3	5.42	4.4–34.2–(14.2)
Ca as CaO	17.21	1.1–40.1–(14.8)
Fe as Fe_2O_3	15.56	2.1–30.0–(9.2)
Mg as MgO	2.32	0.02–23.4–(2.4)
S as SO_3	0.46	0.01–12.4–(2.8)
P as P_2O_5	19.47	0.3–26.7–(11.6)
Ti as TiO_2	–	0.3–1.9–(1.1)
Mn as MnO	–	0.03–0.9–(0.3)
Na as Na_2O	0.76	0.01–6.8–(0.9)
K as K_2O	1.78	0.1–3.1–(1.3)
Loss on ignition	4.72	0.2–41.8–(6.1)

[1] Average values (own source), [2] according to Cyr et al. [9]: values: minimum–maximum–(average), "–" not analyzed.

Table 3 shows results of the author's research on average content of major and trace elements in the tested sewage sludge bottom ash. Trace element average leaching in the water is presented too. The values obtained for bottom ash were compared to the values for fly ash from fluidized bed furnaces.

Determination of trace elements was carried out with the use of standard methods after the Council of the European Union Directive dated 19 December 2002 on the establishment of criteria and procedures for the acceptance to store waste of a given type [24]. Cr, Cd, Ni, and Pb were tested by flameless atomic absorption spectrometry (AAS); Zn and Cu—by flame atomic absorption spectrometry (AAS), As—by inductively coupled plasma atomic emission spectrometry (AES); and Hg—by atomic spectrometry with amalgamation. Leaching was examined for a suspension of waste and deionized water at a liquid to solid ratio of 1000 mL/100 g. Suspension was shaken for 4 h and then, after 24 h, solid/liquid separation was accomplished through 0.45 μm membrane filtration. Solid material was dried and analyzed.

Table 3. Elements in trace concentration in SSAs and leachate.

Heavy Metals	Grate Furnace in Łomża [1]		Fluidized Bed Furnaces [2] Content in Dry Mass (mg kg^{-1} d. m.)
	Content in Dry Mass (mg kg^{-1} d. m.)	Content in Leachate (μg dm^{-3})	
As	0.002	0.03	0.4–726–(87)
Ba	–	–	90–14600–(4142)
Cd	1.5	2.7	4–94–(20)
Co	–	–	19–78–(39)
Cr	4.2	3.5	16–2100–(452)
Cu	249.5	0.8	200–5420–(1962)
Hg	0.00055	0.009	–
Mn	–	–	300–9000–(3000)
Ni	4.7	32.1	79–2000–(671)
Pb	10.9	16.7	90–2055–(600)
Sb	–	–	35–35–(35)
Sn	–	–	183–617–(400)
Sr	–	–	539–539–(539)
V	–	–	14–66–(35)
Zn	394.6	26.2	1084–10000–(3512)

[1] Average values (own source), [2] according to Cyr et al. [9]: values: minimum–maximum–(average), "–" not analyzed, mg kg^{-1} d. m. = ppm.

The author's study on SSA leaching under static–quasi-dynamic conditions reached through gradual agitation and sedimentation of solids at rest, as seen in Table 3. The average values of the elements in trace concentrations found in fly ash from fluidized bed furnaces are higher than their percentage in uncontaminated soils [25] in almost all cases, and therefore, in some cases, they are considered highly toxic [26,27]. The proportion of heavy metals in bottom ash from sludge incineration in grate furnaces is much lower than their content in fly ash from fluidized bed furnaces. However, cadmium, copper, and zinc contents are exceeded in uncontaminated soils. Copper exceeds this range two-fold and zinc three-fold. The high content of copper and zinc in the waste are associated with the dominance of these elements in municipal wastewater and sewage sludge [28]. In the analyzed aqueous extract, only lead concentration insignificantly exceeds the one most frequently quoted for natural soil solutions or groundwater [25]. Despite the high content of copper and zinc, their leaching was not high, as found also in the case of ash from fluidized bed combustor [28]. Białowiec et al. [29] explained how SSA low susceptibility to leaching of heavy metals is caused by the high pH ranging from 8.55 to 11.29.

Unlike combustion of conventional fuel, incineration of sewage sludge is characterized by high water content, which affects the features of obtained products of combustion. For example, class F coal fly ash contains amorphous phase (the enamel) and crystalline phase (mainly quartz, mullite, magnetite, and hematite). At high combustion temperatures 1500–1700 °C, hollow spherical grains form [30]. In contrast, sewage sludge, consisting of one third of inorganic matter, forms particles of ash after combustion at 800–900 °C [31]. The SSA is dominated by irregular grains with strongly developed surfaces. Spherical or rectangular grains are extremely rare [32,33]. Crystalline phases are formed by quartz and, in some cases, calcium phosphate (whitlockite or hydroxyapatite), calcium sulphate, iron oxides, and feldspars. The amorphous phase is 50–74% of the total ash [9].

Figure 1 presents Scanning Electron Microscope (SEM) images of sewage sludge bottom ash taken from grate furnace. Spherical grains are not observed, material is mostly amorphous sinter—porous aluminosilicate with quartz glass, silica, and trace concentrates. The only crystalline phase that has been observed is hematite.
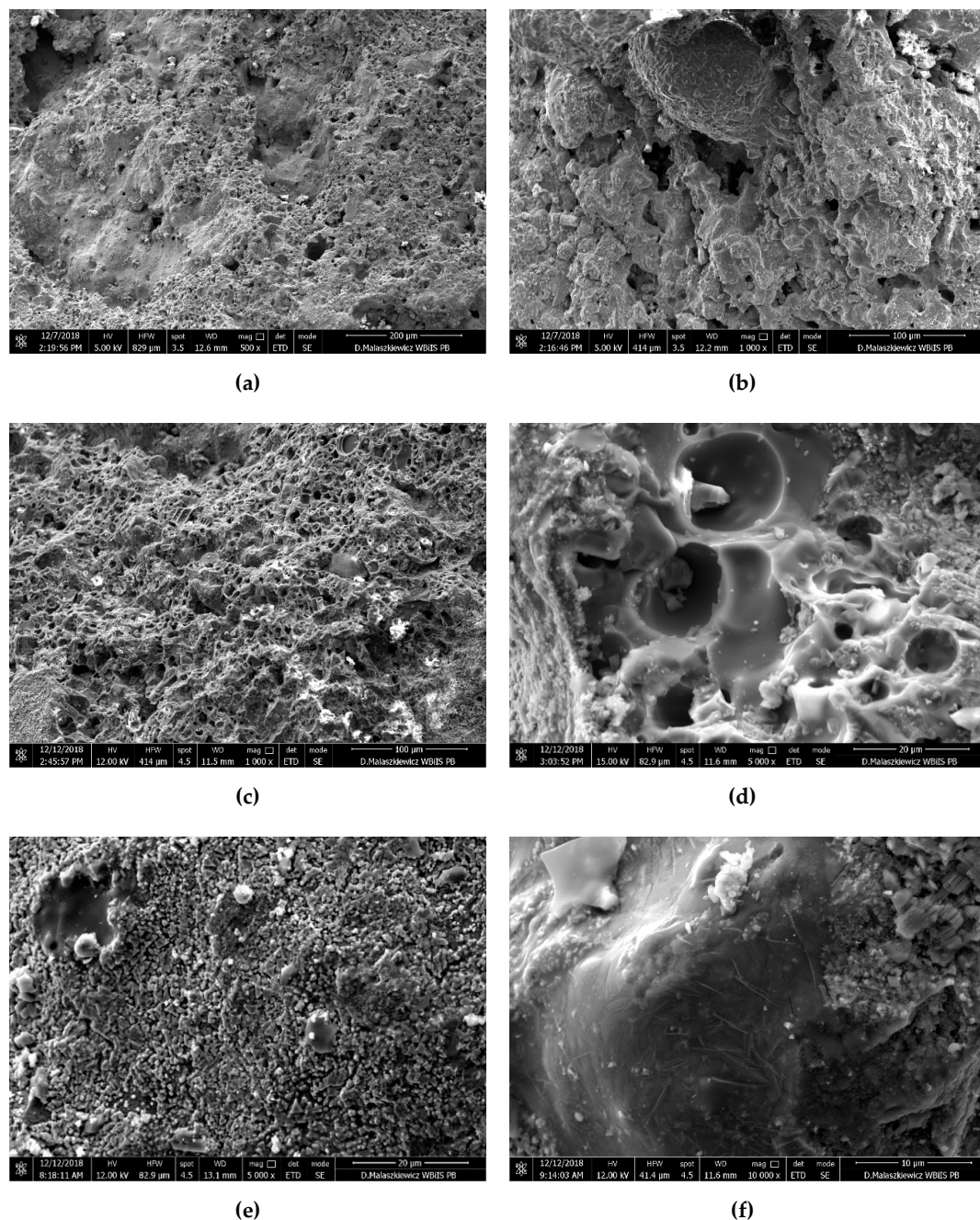
Figure 1. Scanning Electron Microscope (SEM) images of the porous sewage sludge bottom ash: (**a**) a general view of smooth and porous surface 500×, (**b**) porous natural surface 1000×, (**c**) porous fractured surface 1000×, (**d**) silica SiO_2 5000×, (**e**) secondary hematite Fe_2O_3 5000×, (**f**) quartz glass SiO_2.

2.2. Methodology

In 1981, the Road and Bridge Research Institute in Poland issued guidelines on using coal fly ash and bottom ash mixture in road embankments [34], allowing the waste from burning anthracite, bituminous, or lignite coal with specific features to construct the road embankments, taking into account the basic requirements such as waste grading, loss on ignition, and maximum dry density; the guidelines also included the internal angle of friction, the California Bearing Ratio (*CBR*) value after soaking, swelling, as well as supplementary requirements—passive capillarity and SO_3 content. The conditions were amplified in Polish Standard on earthworks as the necessary criteria to use this waste.

The condition for use of waste is its incorporation in a dry place or isolation from the water. When the groundwater table is at a depth of less than 1.0 m below the embankment construction, sealing layer of a thickness of ≥0.5 m must be applied. The insolation layer can be replaced with the geomembrane. Top layer of the embankment (the freezing zone) should be stabilized with the binders or a geomembrane covered with 10 cm layer of sand. The embankment slopes should be protected with anti-erosion cover until the vegetation has formed. In the case of low-level water, when the groundwater table is at a depth greater than the capillary rise of water, the waste can be laid directly on the subsoil. During the formation of embankments, the most important factor is the waste density. To sum up, bottom ash with specific properties is allowed for utilization in all layers of road embankments under the condition that they remain in places isolated from groundwater and rainwater.

To determine the properties of sewage sludge bottom ash (SSA) the methodology used in building soils tests was adopted. Tests were carried out on SSA in the natural state and the mixture of SSA and sand composed in a volume ratio of 3:7. This value was recommended in the Technical Approval [35] for filling material by Polish Member of the European Organization for Technical Assessment (EOTA). SSA and mixture of SSA and sand are shown in Figure 2.

Figure 2. SSA (on the left) and SSA and sand mix (on the right).

3. Results and Discussion

3.1. Physical Parameters

3.1.1. Grading

On the basis of sieve analysis, it was stated that the sewage sludge bottom ash corresponds to coarse-grained soil from gravel to gravel and sand mix, which, according to European classification EN ISO 14688-2: 2018 [36], corresponds to the coarse soil from mixed-grained soil—gravelly sand (grSa) to gravel (Gr). The waste in nearly all ranges may be regarded as a well-compacted material, and thus useful for the construction of embankments of the types from multi-graded to medium-graded soil. The coefficients calculated on the basis of the shape of grading curve are:

Coefficient of uniformity (C_U):

$$C_U = D_{60}/D_{10} = 3.33 - 7.27, \tag{1}$$

and Coefficient of curvature (C_C):

$$C_C = D_{30}{}^2/D_{10} \cdot D_{60} = 1.02 - 1.20 \tag{2}$$

where D_n is an equivalent grain diameter for which n% of the soil by weight is finer.

The range of waste grading curves is shown in Figure 3. The grain-size distribution curve of the waste mixture with sand in a volume ratio of 3:7 is also shown in Figure 3. The mixture corresponds to coarse-grained soil–gravel and sand mix, which, according to the European standard EN ISO 14688-2: 2004, corresponds to gravelly sand (grSa). The mixture of waste with sand should be assessed with respect to the shape of grading curve (C_U = 8.82, C_C = 0.90) as a medium-graded soil.
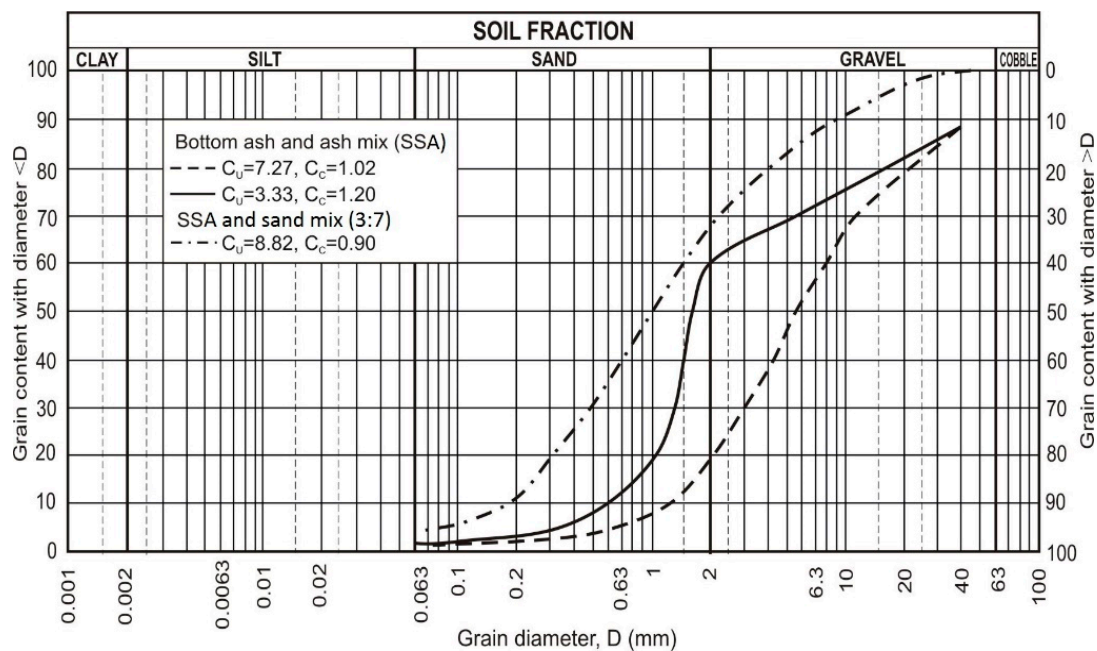

Figure 3. Grain-size distribution of SSA (grading range) and mixture of SSA and sand in a 3:7 ratio.

The sand equivalent value determined in the study is the percentage ratio of the volume fractions corresponding to fractions of sand and gravel and, partly, to the volume of all the material. Due to the coarseness of waste, the study was completed only after five-fold compaction of the same sample of SSA in the Proctor mold, for which the sand equivalent was 75.

Grading of fly ash generated in fluidized bed furnaces differs significantly from the waste from grate combustors. Although typical maximum particle size for SSA from fluidized beds can be up to 700 μm (D_{50} of 8–263 μm) [9,31], SSA from the grate furnace tested in this study was much coarser, with particles up to 40 mm (i.e., 40,000 μm) and a D_{50} of 1.6–6 mm (i.e., 1600–6000 μm). The bottom ash from combustion in the mechanical grate furnace manifests much coarser particle granulation, which makes them the preferred material from the viewpoint of geotechnical applications.

3.1.2. Density of Solid Particles

Determination of density of solid particles (ρ_s) was made using a pycnometer (flask) with water and venting through boiling. This European parameter corresponds to the value of dimensionless specific gravity of soil. The ρ_s average values should be interpreted as the apparent density of solid particles—with closed pores. In the case of SSA the resulting density range was 2.55–2.57 Mg m^{-3}, and the average value 2.56 ± 0.02 Mg m^{-3}. The ρ_s value is similar to the density of fly ash from fluidized bed furnaces, which is 2.46–2.56 Mg m^{-3} [28]. For SSA and sand mix average value of ρ_s equaled 2.62 Mg m^{-3}.

Density of solid waste particles is less than that of mineral soils with a similar granulation, which is 2.65 Mg m^{-3}.

3.1.3. Passive Capillarity

Passive capillarity is the value of the vacuum measured in centimeters of water, where the air permeates through the soil sample slightly densified by kneading with a finger. The vacuum head is considered an important factor that describes the ground sensitivity to frost. The resulting value of passive capillarity of shredded waste in an air-dry condition is less than 1.00 m; the waste is therefore considered as non-frost heaving. A similar value was also obtained for the mixture of sand and SSA. These values were expected because of coarse grain size of tested materials.

3.1.4. Compaction Parameters

Laboratory test of compaction involves compacting the soil in a standardized manner with different water content (w), the application of resulting dry density values (ρ_d) onto the graph showing the relationship $\rho_d(w)$, and estimation values of optimum water content (w_{opt}) and maximum dry density ($\rho_{d\ max}$). The test was performed by the Standard Proctor method (SP). Each point of compaction curve was determined for a separately prepared specimen because it was found that the samples of repeatedly compacted waste could not be considered as representative because of the susceptibility of grains to crushing [37,38]. Before compaction, sample sieving should be done because bottom ash contains oversize particles to be tested in the Proctor mold (>10 mm); next, the dry density and water content values have to be corrected.

Compaction curve of SSA, when the same material was tested only once in comparison with the line of saturation degree $Sr = 1$, is shown in Figure 4.
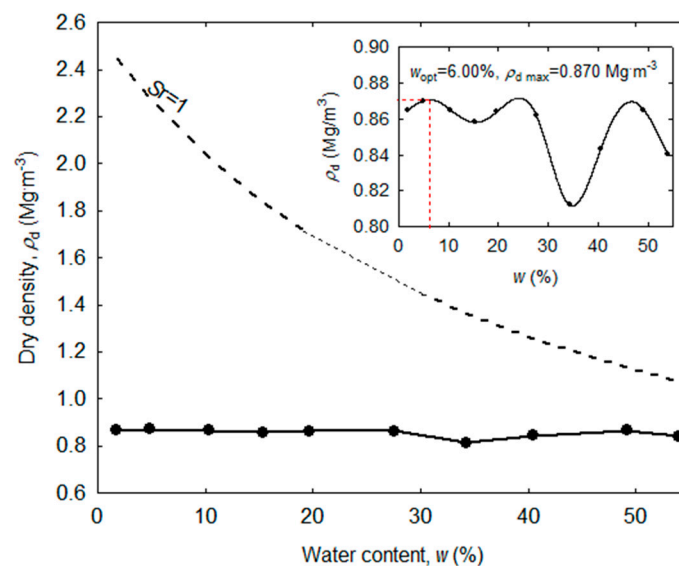

Figure 4. Compaction curve in comparison to line of saturation degree $Sr = 1$ and fragment of compaction curve on different scale.

Compaction parameters resulting from the curve are: $w'_{opt} = 6.00\%$, $\rho'_{d\ max} = 0.870$ Mg m^{-3}. Because the studied sample contained oversize particles (>5%), the parameter values were calculated according to formulas:

$$w_{opt} = (1 - x)w'_{opt} \tag{3}$$

$$\rho_{d\ max} = \frac{\rho_s \times \rho'_{d\ max}}{\rho_s - x(\rho_s - \rho'_{d\ max})} \tag{4}$$

where x is the mass ratio of the grain on the 10 mm sieve to a total weight of the sample.

The calculated values of compaction parameter for real waste, w_{opt} and $\rho_{d\ max}$, are then: $w_{opt} = 3.14\%$, $\rho_{d\ max} = 1.265$ Mg m^{-3}. Low value of dry density is a result of the material porosity, which is visible in Figures 1 and 2.

Changes to granulation of waste grains sized <10 mm were verified after their five-fold dynamic compaction by SP method. Multiple compacting of the same sample of SSA leads to a significant change in its granulation. Grain-size distribution curves of waste before and after compaction differ most significantly in the case of a 2 mm sieve; the difference ranges about 35%.

Laboratory compaction of SSA by the SP method is not very effective, even when considering the ρ_s value of waste, lower than in the case of mineral soil, and its high porosity. Void ratio (e) of grains <10 mm, compacted at the optimum water content is 1.942. However, the plateau graph of SSA compaction curve and high values of dry density of waste compacted in air-dry state, facilitate the embedding of waste in the earthworks.

A comparative study was conducted on $\rho_{d\ max}$ of waste dried into a solid mass by vibration. The study was conducted compacting the waste on the VeBe vibrating table for the duration of 1 min and checking the density after subsequent 0.5 min [39]. Dry density at maximum compaction ($\rho_{d\ max}$) was 0.940 Mg m^{-3}, with $e = 1.723$. As a result of the higher value $\rho_{d\ max}$ of waste received during the vibratory compaction, the vibratory compaction of waste needs to be taken into account during the earthworks.

The tested SSA and sand mixture are distinguished by a compaction curve typical for soil. Compaction parameters of a mixture compacted by the SP method were as follows: $w_{opt} = 15.50\%$, $\rho_{d\ max} = 1.560$ Mg m^{-3}.

3.1.5. Swelling Due to Water Ingress

Soil swelling consists of the increase of pore volume in the soil, which is a result of the increase of water content in the soil. The swell ratio values (*SI*) were calculated by the following formula:

$$SI = \frac{h_S - h_0}{h_0} \cdot 100\% \tag{5}$$

where h_S is the height of specimen after swelling, and h_0 is the initial height of specimen.

Tests were performed on both materials compacted at water contents approximately equal to w_{opt} by the SP method in *CBR* molds, after four days of soaking the samples with water (after maximum swelling) under a consolidation load equaled 2.44 kPa (recommended as the minimum load in the ASTM D 1883) [40]. The following swelling values for SSA were obtained: the mean value of *SI* = 0.20%, and the range of results was 0.17–0.23%. The increase in swelling was observed only during the first day from the start of soaking.

In the case of the tested mixture of sand and SSA, practically no swelling was observed—the mean value of *SI* amounted to 0.005%, and the range of results was 0.00–0.01%. It can be confirmed that the compacted waste does not tend to swell at minimum load.

3.2. Mechanical Properties

3.2.1. Shear Strength

Soil shear strength is its resistance to shearing stress in a considered point of ground. The soil resistance value (τ_f) is determined by the generalized Coulomb's law formula:

$$\tau_f = \sigma \cdot tan\varphi + c \tag{6}$$

where τ_f is the soil resistance at the moment of shearing, σ the shear stress to destruction plane—normal stress, φ the angle of internal friction, and c the cohesion (soil cohesion resistance).

Waste strength tests were carried out in direct shear apparatus, with the forced shear plane. Samples with moisture contents close to w_{opt} were compacted by vibrating directly in the direct shear apparatus box (12 × 12 cm) to a density corresponding to the maximum densities of samples compacted by the SP method. Samples of waste were sheared after the initial consolidation with no drainage of water during the process of shearing at a ratio of 1 mm/min. Figure 5 shows scheme of direct shear apparatus box and obtained relationships of $\tau_f(\sigma)$ for the SSA and the mix of SSA and sand.
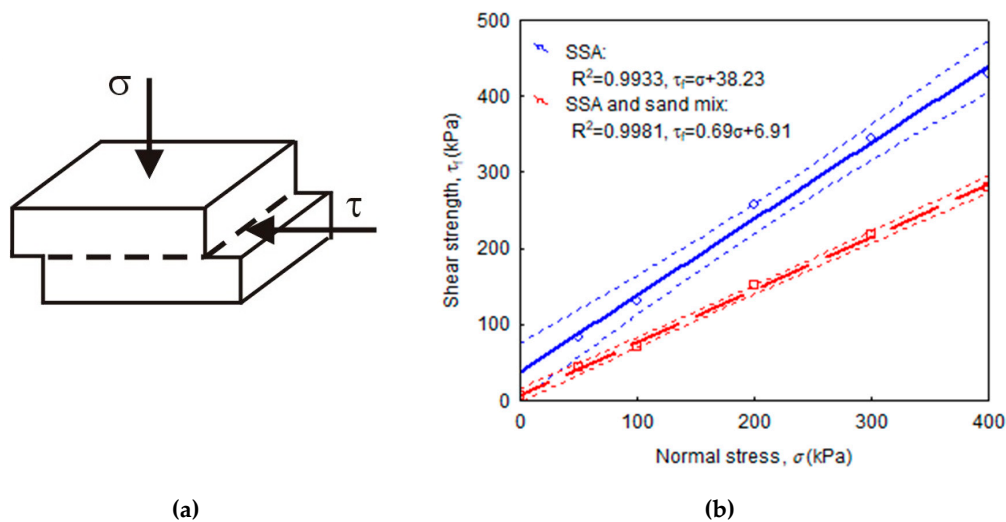

(a)	**(b)**

Figure 5. Shear strength of SSA or SSA and sand mix: (**a**) schematic diagram of direct shear apparatus, (**b**) shear strength test results.

The cohesion resistance value results from the acceptance of the linear approximation of the failure envelope of soil and amounts to 38.23 kPa in the case of SSA and 6.32 kPa for the mixture. The angle of internal friction of waste is 45° and 34.7°, respectively.

The waste compacted at w_{opt} is characterized by high values of the angle of internal friction and cohesion resistance. Greater shear strength of SSA in comparison with the mixture is a result of the presence of a larger number of porous, angular grains, and coarser grain-size distribution. The resulting strength parameters are higher or similar to those of mineral soils of corresponding grading for both: the SSA and SSA mixture with sand. For example, the angle of internal friction of gravelly sand and gravel is about 36–42°, depending on state of compaction.

3.2.2. California Bearing Ratio

Resistance to failure is estimated on the basis of CBR test results. The CBR is expressed as the percentage ratio of unit force (p) that has to be applied so that a standardized circular piston may be pressed into a soil specimen to a definite depth at a rate of 1.25 mm/min, and standard force, corresponding to unit force (p_s) necessary to press the piston at the same rate into the same depth of a standard compacted well-graded crushed stone:

$$CBR = \frac{p}{p_s} 100\% \tag{7}$$

Tests were performed on the samples without prior soaking and, for samples soaked in water, to maximal swelling [40]. The time of soaking should be not shorter than four days. The samples were compacted in CBR molds by the SP method at moisture contents on the dry side of optimum. The penetrated samples were loaded 2.44 kPa. The results are shown in Table 4. The values of CBR for SSA compacted at optimum water content are similar to the values obtained with mineral soils of corresponding grading, and higher in the case of a mixture with sand. The CBR values decrease after a

four-day soaking with water when compared with the samples tested immediately after compaction: by about 30% in the case of SSA and less than 20% for the mixture of SSA with sand.

Table 4. California Bearing Ratio (CBR) test results for unsoaked and soaked SSA or SSA and sand mix.

Parameter	Unit	SSA		SSA and Sand Mix	
		Without Soaking	Soaked 4 Days	Without Soaking	Soaked 4 Days
Average value of *CBR*	%	16.3	11.0	33.6	27.6
CBR range	%	13.3–21.9	8.9–13.1	30.7–36.4	26.9–28.3
Average value of *w*	%	0.87	0.87/44.60 *	11.82	12.06/17.71 *
Average value of ρ_d	Mg m^{-3}	0.898		1.538	

* Water content at compaction/water content after soaking.

3.3. SSA and SSA and Sand Mix Properties Summarising

The results of research on product of combustion of municipal sewage sludge in Łomża in comparison with the standard requirements for coal fly ash and bottom ash mixture assembled into road embankments are shown in Table 5.

Table 5. Polish standard requirements for classes F and C fly ash and bottom ash mix to be built-in road embankments in comparison to SSA or SSA and sand mix.

No.	Standard Requirements		SSA	SSA and Sand Mix
	Basic Requirements			
1.	Grading (%):			
	→fraction of sand and gravel	≥35	40.46–81.84	68.5
	→content of grains < 0.075 mm	≤75	1.36–2.0	6.3
2.	Sand equivalent:			
	→in natural state	≥15	–	–
	→after 5th compaction in Proctor's mold	≥10	75	–
3.	Loss of ignition (%)	≤10	4.72	1.50
4.	Maximum dry density (Mg m^{-3})	≥1.0	1.265	1.560
5.	*CBR* after 4 days of soaking (%)	≥10	11.0	27.6
6.	Linear swelling (%)			
	→without loading	≤2.0	–	–
	→under loading 3 kPa	≤0.5	0.20	0.005
	Supplementary requirements			
7.	Angle of internal friction (°)	≥20	45.0	34.7
8.	Passive capillarity (m)	≤2.00	<1.00	<1.00
9.	Content of SO$_3$ (%)	<3.0	0.46	0.14

"–" not analyzed.

Analysis of the possibilities of using waste proved that the sewage sludge bottom ash, as well as its mixture with sand, meet all the requirements for waste built-in earth structures. Coarse SSA suits all conditions resulting from its grain-size distribution: grading, sand equivalent, and passive capillarity. Angle of internal friction is a result of graining, structure of grains, and resistivity of grains on shearing. The CBR value—high directly after compaction—decreases after soaking process, which is a result of grain softening under the influence of water (SSA is not particularly swelling material). SSA incorporated in earth structures should be protected against water. Mixing SSA with sand, in a volume ratio of 3:7, improves properties of SSA that can be decreased under the influence of wetting, like swelling and CBR after four days of soaking.

4. Conclusions

(1) The test results of physical and mechanical properties and chemical composition indicated the possibility of using sewage sludge bottom ash (SSA) as a material for sustainability-related

applications in civil engineering. The tested sewage sludge bottom ash meets the standard requirements formulated for coal combustion by-products assembled into road embankments. These requirements are fulfilled also in the case of a mixture of SSA with sand in a volume ratio of 3:7, with higher CBR, but lower shear strength compared to the SSA.

(2) Because the CBR value of SSA after soaking with water is reduced by 30% and displays relatively low CBR values of soaked waste, it should be assembled in a space isolated from groundwater and rainwater. This notion is also supported by the possibility of leaching of heavy metals from the SSA mass, the content of which in the waste is higher than in uncontaminated soils.

(3) Embedding of SSA should be carried out by the guidelines on incorporating coal fly ash and bottom ash mixtures in road embankments. The lower isolation layer at a high groundwater table, and an upper layer of the embankment in the freezing area should be protected by chemical stabilization.

(4) The CBR value for SSA and sand mixture is higher than that of the SSA alone, and it undergoes a smaller reduction after a four-day soaking. Because the mixture contains only 30% of waste, and thus lower content of heavy metals, the mix incorporation directly into layers of the embankment can be deliberated.

(5) The examined sewage sludge bottom ash from the combustion of sludge in a grate furnace has a much coarser granulation than the fly ash generated from the incineration of sludge in fluidized bed furnaces. They are therefore the preferred material for use in earthworks than waste generated during combustion in a fluidized bed. The percentage of trace elements in the waste from sludge incineration in grate furnaces is much lower than their content in the fly ash from fluidized bed furnaces and their leaching was not high.

(6) As a result of the shortage of data concerning the geotechnical properties of the sewage sludge bottom ash, further laboratory and field tests should be conducted to confirm the suitability of the waste for earthworks.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Werther, J.; Ogada, T. Sewage sludge combustion. *Prog. Energ. Combust.* **1999**, *25*, 55–116. [CrossRef]
2. Werle, S.; Wilk, R.K. A review of methods for the thermal utilization of sewage sludge: The Polish perspective. *Renew. Energy* **2010**, *35*, 1914–1919. [CrossRef]
3. Takaoka, M.; Takeda, N. Mercury emission from sewage sludge incineration in Japan. *J. Mater. Cycles Waste Manag.* **2012**, *14*, 113–119. [CrossRef]
4. Werle, S.; Dudziak, M. The assessment of sewage sludge gasification by-products toxicity by ecotoxicological test. *Waste Manag. Res.* **2015**, *38*, 686–703.
5. Eurostat's Database. Sewage Sludge Production and Disposal. Available online: http://ec.europa.eu/eurostat/web/products-datasets/-/ten00030 (accessed on 8 November 2019).
6. Monitor Polski (Official Journal of the Republic of Poland). Government Resolution No. 217 of 24 December 2010 on National Waste Management Plan 2014 (in Polish). Available online: http://monitorpolski.gov.pl/MP/2010/s/101/1183 (accessed on 8 November 2019).
7. Smol, M.; Kulczycka, J.; Henclik, A.; Gorazda, K.; Wzorek, Z. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *J. Clean. Prod.* **2015**, *95*, 45–54. [CrossRef]
8. Cieślik, B.M.; Namieśnik, J.; Konieczka, P. Review of sewage sludge management: Standards, regulations and analytical method. *J. Clean. Prod.* **2015**, *90*, 1–15. [CrossRef]

9. Cyr, M.; Coutand, M.; Clastres, P. Technological and environmental behavior of sewage sludge ash (SSA) in cement-based materials. *Cem. Concr. Res.* **2007**, *37*, 1278–1289. [CrossRef]

10. Baeza-Brotons, F.; Garcés, P.; Payá, J.; Saval, J.M. Portland cement systems with addition of sewage sludge ash. Application in concretes for the manufacture of blocks. *J. Clean. Prod.* **2014**, *82*, 112–124. [CrossRef]

11. Lynn, C.J.; Dhir, R.; Ghataora, G.S.; West, R.P. Sewage sludge ash characteristics and potential for use in concrete. *Constr. Build. Mater.* **2015**, *98*, 767–779. [CrossRef]

12. Naamane, S.; Rais, Z.; Taleb, M. The effectiveness of the incineration of sewage sludge on the evolution of physicochemical and mechanical properties of Portland cement. *Constr. Build. Mater.* **2016**, *112*, 783–789. [CrossRef]

13. Chen, Z.; Poon, C.S. Comparative studies on the effects of sewage sludge ash and fly ash on cement hydration and properties of cement mortars. *Constr. Build. Mater.* **2017**, *154*, 791–803. [CrossRef]

14. Durante Ingunza, M.P.; de Araújo Pereira, K.L.; dos Santos Junior, O.F. Use of sludge ash as a stabilizing additive in soil-cement mixtures for use in road pavements. *J. Mater. Civil Eng.* **2015**, *27*. [CrossRef]

15. Chen, L.; Lin, D.F. Stabilization treatment of soft subgrade soil by sewage sludge ash and cement. *J. Hazard. Mater.* **2009**, *162*, 321–327. [CrossRef] [PubMed]

16. Lin, D.F.; Lin, K.L.; Hung, M.J.; Luo, H.L. Sludge ash/hydrated lime on the geotechnical properties of soft soil. *J. Hazard. Mater.* **2007**, *145*, 58–64. [CrossRef] [PubMed]

17. Cheesemen, C.R.; Virdi, G.S. Properties and microstructure of lightweight aggregate produced from sintered sewage sludge ash. *Resour. Conserv. Recycl.* **2005**, *45*, 18–30. [CrossRef]

18. Celary, P.; Sobik-Szołtysek, J. Vitrification as an alternative to landfilling of tannery sewage sludge. *Waste Manag.* **2014**, *34*, 2520–2527. [CrossRef]

19. Merino, I.; Arévalo, L.F.; Romero, F. Characterization and possible uses of ashes from wastewater treatment plants. *Waste Manag.* **2005**, *25*, 1046–1054. [CrossRef]

20. Tenza-Abril, A.J.; Saval, A.M.; Cuenca, A. Using sewage-sludge ash as filler in bituminous mixes. *J. Mater. Civil Eng.* **2015**, *27*. [CrossRef]

21. Dhir, R.K.; Ghataora, G.S.; Lynn, C.J. *Sustainable Construction Materials: Sewage Sludge Ash*; Woodhead Publishing—Elsevier Ltd.: Cambridge, UK, 2017.

22. Gomes Correia, A.; Winter, M.G.; Puppala, A.J. A review of sustainable approaches in transport infrastructure geotechnics. *Transp Geotech.* **2016**, *7*, 21–28. [CrossRef]

23. Zabielska-Adamska, K. Product of municipal sewage sludge incineration as an anthropogenic soil (in Polish). *Rocz. Ochr. Sr./Annu. Set Environ. Prot.* **2015**, *17*, 1286–1305.

24. Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC (2003/33/EC). 2002. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32003R1882 (accessed on 8 November 2019).

25. Kabata-Pendias, A.; Pendias, H. *Trace Element Biogeochemistry (in Polish)*; Sci. Publ. House PWN: Warsaw, Poland, 1993.

26. Fytili, D.; Zabaniotou, A. Utilization of sewage sludge in EU application of old and new methods—A review. *Renew. Sustain. Energy Rev.* **2008**, *12*, 116–140. [CrossRef]

27. Inoue, K.; Uchida, T. Reduction of hazardous elements contained in sewage sludge incineration ash. *J. Mater. Cycles Waste Manag.* **2017**, *19*, s10016–s10163. [CrossRef]

28. Kępyś, W.; Pomykała, R.; Pietrzyk, J. Properties of fly ash from thermal conversion of municipal sewage sludge. *J. Pol. Miner. Eng. Soc.* **2013**, *31*, 11–18.

29. Białowiec, A.; Janczukowicz, W.; Krzemieniewski, M. Possibilities of utilisation of fly ash from sewage sludge thermal treatment in the aspect of legal regulations (in Polish). *Rocz. Ochr. Sr./Annu. Set Environ. Prot.* **2009**, *11*, 959–971.

30. Zabielska-Adamska, K. *Fly Ash as a Material for Constructing Sealing Layers (in Polish)*; Theses and Dissertation 136; Publ. House of Bialystok Univ. Techn.: Bialystok, Poland, 2006.

31. Donatello, S.; Cheeseman, C.R. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Manag.* **2013**, *33*, 2328–2340. [CrossRef]

32. Horiguchi, T.; Fujita, R.; Shimura, K. Applicability of controlled low-strength materials with incinerated sewage sludge ash and crushed-stone powder. *J. Mater. Civil Eng.* **2011**, *23*, 767–771. [CrossRef]

33. Kosior-Kazberuk, M. Application of SSA as partial replacement of aggregate in concrete Polish. *J. Environ. Stud.* **2011**, *20*, 365–370.

34. Słupski, W. *Technology of Road Embankments from Power Engineering Wastes (Guidelines in Polish)*; Road Bridge Res. Institute: Warsaw, Poland, 1981.

35. AT-15-8888/2012. *Guideline for Technical Approval of Mixture of Sand and Bottom Ash "Filling mixture from MPWiK Łomża" (in Polish)*; ITB: Warsaw, Poland, 2012.

36. EN ISO 14688-2: 2018. *Geotechnical Investigation and Testing. Identification and Classification of Soil. Part 2: Principles for a Classification*; ISO: Geneva, Switzerland, 2018.

37. Zabielska-Adamska, K. Laboratory compaction of fly ash and fly ash with cement additions. *J. Hazard. Mater.* **2008**, *151*, 481–489. [CrossRef]

38. Patakiewicz, M.A.; Zabielska-Adamska, K. Crushing of non-cohesive soil grains under dynamic loading. *Procedia Eng.* **2017**, *89*, 80–85. [CrossRef]

39. Zabielska-Adamska, K. *Anthropogenic Soils. Compaction and Properties of Compacted Soils (in Polish)*; Polish Academy of Sciences: Warsaw, Poland, 2019.

40. ASTM D 1883-16. *Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils*; ASTM International: West Conshohocken, PA, USA, 2016.