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8 **1. Introduction**

9

10 Sewage sludge (SS), produced in every sewage sludge treatment plant, can become a
11 significant source of energy, heat, or chemical substances e.g. fertilizers, macro- and
12 microelements. Due to the presence of mentioned nutrients, in many countries, SS constitutes
13 a valuable substrate for the improvement of arable land quality or remediation of degraded
14 areas, which is a cost-effective and environmentally friendly solution. Annually,
15 around 11.5 Mt of SS dry matter (DM) is produced in European Union countries
16 (Vouk et al., 2018). It is estimated that the amount of SS produced in these countries by 2020
17 will have increased to about 13 Mt DM (D. Vouk et al., 2017). The available SS disposal
18 methods are limited by a series of constantly updated legal acts (Cieślik et al., 2015). For this
19 reason, existing methods are being replaced in favour of more modern ones, that are consistent
20 with new legal requirements. One of the legal act in the European Union regarding the SS is
21 Council Directive (91/271/EEC) of 21 May 1991 (European Commission, Council Directive of
22 21 May, 1991) according to which the SS should be treated as a product for further
23 development. For this reason, some of the existing management techniques (e.g. storage, soil
24 reclamation, fertilizer production) are even forbidden (Kacprzak et al., 2017).

25 Sewage sludge management methods can be divided into two main groups: biological and
26 thermal. Biological methods such as composting or anaerobic digestion are used less frequently
27 due to the increasing legal requirements for the quality of the processed SS which usually
28 requires further processing (Cieślik et al., 2015). Thermal methods that become a promising
29 alternative include the incineration, pyrolysis and vitrification. The treatment of SS by pyrolysis
30 generates less pollution than incineration, but the main barrier is the complexity of the process,
31 which generates significant maintenance costs. Vitrification, belonging to the high-temperature
32 process (1000-1600 °C), ensures the production of completely environment-neutral material.
33 However, due to high energy consumption, it also requires high financial expenditures
34 (Samolada and Zabaniotou, 2014). In addition, during the vitrification, specific elements
35 species which could be described as volatile in certain conditions (As, Cd, Pb, Se, Hg)
36 (Elled et al., 2007), can be released into the environment so there is a need for continuous

37 monitoring of the process. Moreover, the variety of by-products streams, which have to be
38 managed, also should be considered (Hernandez et al., 2011).

39 Due to the diverse composition of SS and significant amounts of potentially harmful
40 substances contained in it (drugs, pharmaceuticals (Díaz-Cruz et al., 2009; Nieto et al., 2010))
41 and heavy metals (Lu et al., 2016; Yang et al., 2017)), this waste is usually utilized by
42 incineration. The process ensures complete decomposition of pathogens, organic matter, and
43 odoriferous substances. Additionally, the volume of SS is significantly reduced,
44 even by 90 - 95%, and its mass by about 70% compared to the state before the process
45 (Lewkowska et al., 2016; Lynn et al., 2015; Tashima et al., 2017). The disadvantage of the
46 incineration process is the concentration of potentially harmful elements and unavoided
47 production of solid residues (dust and ash), which must be properly managed.

48 Positive aspects related to the incineration process make it an increasingly common
49 management technique. Around 22% of SS in the European Union is incinerated
50 (D. Vouk et al., 2017) which gives about 0.77 Mt solid waste per year. Germany itself produces
51 about 0.3 Mt of SSA (Krüger and Adam, 2014). It was estimated that the amount of SSA
52 generated in the USA is about 0.54 Mt (Cyr et al., 2007) while in Japan, the management
53 problem is related to significant quantities of obtained SSA (about 0.24 Mt per year) and limited
54 land availability (Donatello and Cheeseman, 2013). It is worth noting that the presented values
55 refer only to the amount of the produced ash, i.e. one of the solid residue fractions produced
56 during the thermal utilization process. As a result of the exhaust gas stream purification, because
57 of the use of various sorbents (Kijo-Kleczkowska et al., 2015; Liu et al., 2015) a second waste
58 fraction is also formed – dust. The dust to ash ratio may vary from 5% to 60%, depending on
59 the technology (Lapa et al., 2007; Marani et al., 2003), and in most publications, related to SSA
60 management, the problem of dust management is usually completely neglected.

61 The quantities of generated SSA in comparison to ash from the energy industry (coal
62 combustion residuals) are about 100 times smaller (about 115 Mt for UE and US countries)
63 (Belviso, 2018; Cyr et al., 2007). However, the management of significant amounts of coal
64 combustion residuals is not considered as a problem, because it is a commonly used mineral
65 addition in cementitious binders. Due to many similarities in SSA production and similar
66 composition to coal fly ash, research on the use of SSA in the construction industry is often
67 carried out. Sewage sludge ash is treated often as a replacement for a binder (Chen et al., 2018;
68 Kappel et al., 2017; Dražen Vouk et al., 2017) or as a mineral addition (Baeza-Brotons et al.,
69 2014; Jamshidi et al., 2012; Záleská et al., 2018) to both mortars and concretes. Mentioned
70 waste can be also used in alkali-activated binder mixtures as a reaction precursor.

71 (Chakraborty et al., 2017; Istuque et al., 2016; Tashima et al., 2017). Bricks and tiles
72 (Lin et al., 2017, 2016; Mozo and Gomez, 2016), ceramics (Zhang et al., 2015), glassy materials
73 (Borowski, 2015; Celary and Sobik-Szołtysek, 2014) and lightweight aggregates (Cheeseman
74 and Viridi, 2005; Chiou et al., 2006; Lin, 2006) belonging to sintered materials can be also
75 produced with the contribution of SSA, however, these processes also require significant energy
76 demand. The manufactured products, despite eliminating the risk of heavy metals entering the
77 environment, are often characterized by inferior properties e.g. lower compressive strength or
78 higher shrinkage. In addition, the production of such materials requires additional gas treatment
79 systems due to the possible presence of volatile heavy metals and other elements species.

80 Due to the variety of research presented in publications, the complexity of the used waste
81 and the various conclusions regarding the impact of SSA on the properties of cement-based
82 construction products, this article summarizes and presents the latest literature reports related
83 to the use of SSA in cementitious materials. Considering the disadvantages of selected
84 development techniques of both SS and SSA and the fact that SS incineration is currently
85 considered as the Best Available Technology (Kijo-Kleczkowska et al., 2016), the article
86 focuses exclusively on the management of SSA in concretes and mortars based on hydraulic
87 binders. This approach eliminates the possible emission of heavy metals to the environment
88 (which is confirmed by leaching tests) and does not require complicated facilities. However, it
89 is difficult to estimate the cost and profitability of such management technique, because it
90 depends on local situation and circumstances, such as raw materials availability, economy or
91 geography (Spinosa et al., 2011).

92 Literature reports have been described in detail in two main groups: cementitious materials
93 (mortars or concretes), in which SSA is an additive and materials in which SSA is a substitute
94 for the main binder. It was also indicated which of the factors may affect the properties of the
95 end products e.g. the proportion and type of binder, the method of sample preparation as well
96 as the impact of SSA quality on durability properties. Due to the difficulty in clearly
97 determining whether toxic heavy metals contained in SSA are safely immobilized in a cement
98 matrix, results of leaching heavy metals from hardened products are also described.
99 The presented information can be particularly helpful during the design of modern building
100 materials and the analysis of the environmental impact of these materials. Some critical issues
101 are also considered.

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1. Methods and scope

This study focuses on describing SSA management methods and presents the advantages and disadvantages of including mentioned wastes into building materials based on cement binders. A thorough assessment of selected approaches available in the literature has been carried out. Since the subject is still developing in some countries, the review is based on literature from the entire world. The article is based on the scientific literature but not exclusively. Research published in technical journals and book sections was also used.

The article briefly presents the variety of research on the use of SSA in cement building materials, the research on the cement hardening process, the impact of mineral additives on the properties of mortars and concretes, as well as the use of other waste materials in the construction industry. A thorough analysis of the influence of various factors on cement building materials was performed to simplify condensed information on the impact of SSA wastes uses in building materials.

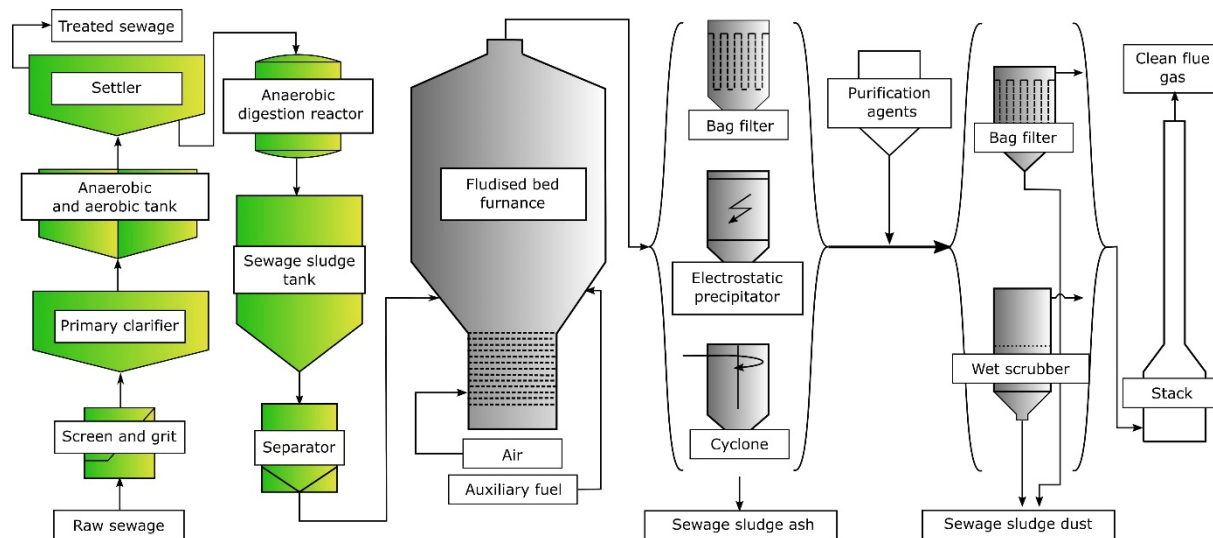
2. The SSA potential in materials based on cement binders

2.1. Characteristics of SSA

Sewage sludge is a residue left after a primary (physical), secondary (biological) and tertiary (chemical) wastewater treatment (Fytily and Zabaniotou, 2008). Some of the produced residues, especially in municipal wastewater treatment plants processing significant amounts of wastewater, are processed by anaerobic digestion. Before incineration, the produced SS is dewatered and dried in order to remove as much water as possible. If the SS calorific value is low (e.g. due to high water content), additional fuel can be used in the incineration process (Wzorek and Tańczuk, 2015). The properly prepared SS is most commonly incinerated in fluidized bed furnaces at a temperature of 850 °C in order to utilize potentially harmful organic fractions. The process can be carried out at higher temperatures to degrade e.g. polychlorinated substances (Wey et al., 2008). Exhaust gases are dedusted in a multi-stage cyclone system, bag filters or electrostatic precipitators, which results in the separation of ash (fly ash). Further gas purification with the use of sorbents, for example, sodium bicarbonate, lime and activated carbon (used for neutralization and removal of harmful organic substances and volatile elemental fractions) generate another fraction of waste – dust or fine fly ash. Both streams of solid residues due to the presence of heavy metals and metalloids have to be properly managed (Kacprzak et al., 2017; Samolada and Zabaniotou, 2014). An example diagram of a sewage

137 sludge incineration system is presented in Figure 1. It is worth noting that the type of used
 138 sorption media may cause differences in the composition of dust obtained during exhaust gas
 139 purification. The elemental composition of dehydrated SS and SSA are also significantly
 140 different, therefore ash fraction constitutes a completely different product (Świerczek and
 141 Cieślík, 2018).

142



143

144 Figure 1. A simplified diagram of a SS thermal treatment plant.

145

146 The main oxides found in SSA, determined mostly using X-ray fluorescence technique
 147 (XRF) include SiO_2 , Al_2O_3 , CaO , Fe_2O_3 , NaO , MgO and P_2O_5 (Lynn et al., 2015). Silicone
 148 oxide minerals (e.g. quartz), whitlockite, mullite, calcium sulphate minerals (e.g. anhydrite),
 149 magnetite, feldspars, and micas belong to the crystalline minerals (shown in Fig. 3) present in
 150 SSA. However, the amorphous phase constitutes about 45 % of the SSA mass (Chen and Poon,
 151 2017; Cyr et al., 2007; Halliday et al., 2012). In addition to the aforementioned main oxides,
 152 SSA contains a number of inorganic heavy metal compounds. Based on the analysis of many
 153 test results, it has been shown that solid residues contain Cd, Cu, Ni, Pb, Cr, Mn, Fe, As, Sb,
 154 Hg at various concentrations. Reduction of the SS volume and mass as a result of incineration
 155 increases the content of heavy metals in the obtained solid residues (Van de Velden et al., 2008).

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157 2.2. Possibilities and limitations related to the use of SSA in cement-based materials

158 The main silicate compounds in cement clinker that are responsible for its hardening are
 159 alite (tricalcium silicate $3\text{CaO}\cdot\text{SiO}_2$) and belite (β -dicalcium silicate – $2\text{CaO}\cdot\text{SiO}_2$). Alite
 160 constitutes about 50%, while belite about 20% of the total mass of clinker. The remainder of
 161 the mass are mostly tricalcium aluminate ($3\text{CaO}\cdot\text{Al}_2\text{O}_3$), and tetracalcium aluminoferrite

162 (4CaO·Al₂O₃·Fe₂O₃) (Li et al., 2018; MacKenzie and Smith, 2002). As a result of the reaction
163 of these substances with water, calcium silicate hydrate and calcium hydroxide are formed. The
164 hydrated calcium silicates commonly described as C-S-H phase (where: C-CaO, S-SiO₂,
165 H-H₂O) may have a various composition, morphology, and degree of crystallization.
166 The introduction of e.g. supplementary cementitious materials (SCM) e.g., fly ash, slags,
167 calcined clays containing aluminium causes the formation of calcium aluminosilicate hydrate
168 C-A-S-H (where: A-Al₂O₃) (Geng et al., 2017; Li et al., 2019). Both mentioned phases are
169 responsible for the strength of the cement paste. However, some minerals from the calcium
170 aluminate hydration system (e.g. CAH₁₀, C₃AH₆) have been shown to have even higher
171 mechanical properties than the C-S-H phases. Despite the low density of C-A-S-H minerals,
172 similar or higher mechanical properties are mainly related to the topology of the mineral
173 network (Geng et al., 2018).

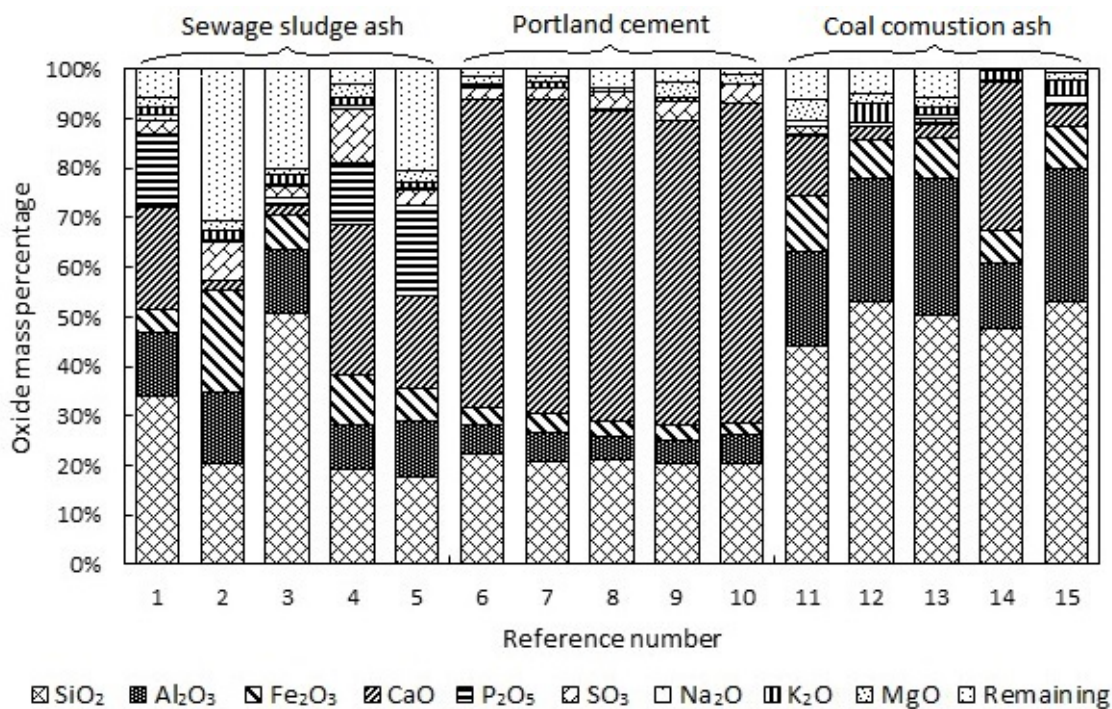
174 It should be noted that the use of SCM is becoming a more and more common procedure
175 aimed at reducing CO₂ emissions and cement consumption. Due to the use of new types of
176 SCM or their blends, the methods for determining technical standards and specific criteria for
177 determining their suitability in building materials also need to be modified/updated.
178 In accordance with ASTM C 618-19, pozzolanic material that can be used in concrete should
179 contain SiO₂, Al₂O₃, and Fe₂O₃ in an amount of 50 - 70% of the total mass of the material.
180 Additionally, such materials generally do not exhibit binding properties, but form stable bonds
181 in the presence of water and Ca(OH)₂ (ASTM, 2003). However, as emphasized by R. Snellings
182 methods for determining SCM activity based on the measurement of the lime consumption or
183 measuring only the strength of the SCM - cement mixture are insufficient. The authors propose
184 the measurement of cumulated heat release, chemical shrinkage, or bound water content, which
185 allows treating a wider range of SCMs as active materials in cement mixtures.
186 (Snellings et al., 2019). The differences in the methods of determining SCM activity in cement
187 mixtures may be related to the lack of uniformity regarding the activity of SSA in research on
188 its use in building materials.

189 The physicochemical characteristics, composition and production technology of SSA, make
190 it similar to the coal ash residuals thus SSA is used as a binder or fine aggregates substitute
191 which has its advantages and disadvantages. The presence of active oxides in SSA, mainly
192 SiO₂, Al₂O₃, Fe₂O₃, CaO can have a positive effect on the hardening of building materials
193 (Chen and Poon, 2017; Sara Naamane et al., 2016). Figure 2 presents a comparison of the main
194 oxides percentage content found in SSA, Portland cement and coal fly ash. The coal fly ash,
195 similar to SSA, includes more Al₂O₃ compared to Portland cement. The presence of this oxide,



196 as well as sulfate and calcium ions, contribute to the formation of calcium sulfoaluminate
 197 hydrates (AFt) e.g. ettringite and calcium aluminate hydrates (AFm) e.g. monosulfoaluminate
 198 (Avet et al., 2019; Balonis, 2019). The AFm phase is characterized by significant chloride
 199 sorption potential, therefore the presence of SSA in concrete may increase its resistance to the
 200 harmful effects of chlorides (Balonis, 2019; Lynn et al., 2015). It is worth noting that SSA in
 201 mortar or concrete can also increase the number of nucleation sites for C-S-H phase formation
 202 (Scrivener et al., 2015).

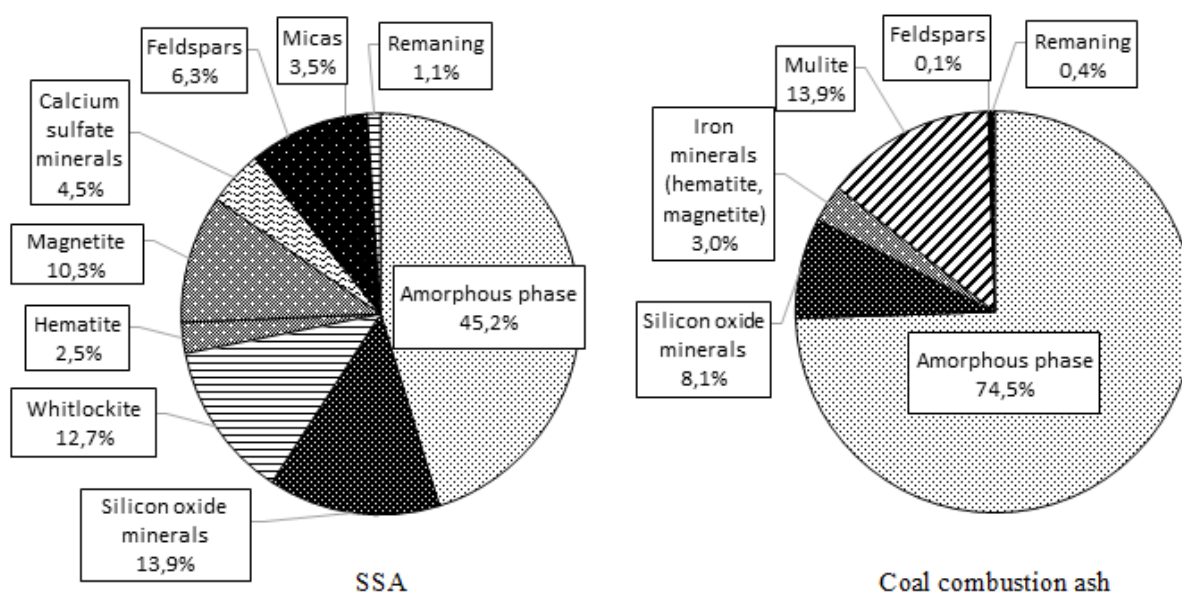
203 An additional benefit associated with the use of SSA is the possibility of immobilizing
 204 heavy metals in the matrix of hydrated phases (K.Kazberuk, 2011; Li et al., 2017). Due to the
 205 characteristic particle-size distribution of SSA (2.5 - 250.0 μm), it can be used as a filler or
 206 substitute for fine aggregate in concrete (Lynn et al., 2015).



207 \square SiO₂ \blacksquare Al₂O₃ \boxtimes Fe₂O₃ \diagup CaO \blacksquare P₂O₅ \boxtimes SO₃ \square Na₂O \blacksquare K₂O \boxtimes MgO \square Remaining
 208
 209 Figure 2. Mass percentage of main oxides in SSA, Portland cement and coal combustion
 210 ash; 1 - (Cyr et al., 2007), 2 - (Tay and Show, 1994), 3 - (Pan et al., 2003), 4 - (Garcés et al.,
 211 2008), 5 - Rutkowska et al., 2018), 6 - (Li and Poon, 2017), 7 - (Tay and Show, 1994),
 212 8 - (Monzo et al., 1997), 9 - (Yusuf et al., 2012), 10 - (Monzó et al., 1996), 11 - (Chen and
 213 Poon, 2017), 12 - (Fernández-Jiménez and Palomo, 2005), 13 - (Jang and Lee, 2016),
 214 14 - (Suksiripattanapong et al., 2015), 15 - (Richardson et al., 2016).
 215

216 Despite the similar ratio of SiO₂ / Al₂O₃ to coal fly ash, the sum of oxides in SSA on the
 217 basis of which material can be classified as pozzolan material is often lower (Fig. 2). It was
 218 reported that SSA exhibit lower pozzolanic activity than ash from coal combustion (Chen and
 219 Poon, 2017; Rutkowska et al., 2020) or other conventional supplementary cementitious material

220 (Mejdi et al., 2020). Figure 3 presents the differences in mineralogical composition between
 221 SSA and coal fly ash. The higher ash activity compared to SSA is associated with a different
 222 composition and the occurrence of an amorphous phase. It is worth adding that the SSA's
 223 mineralogical composition is primarily influenced by the processing temperature of the SS.
 224 That basically means that it is impossible to substitute fly ash with SSA without at least a slight
 225 change in product properties.



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 227
 228 Figure 3. Comparison of the content of the main mineral phases determined by the XRF
 229 technique in SSA and ash from coal combustion (Chen and Poon, 2017; Cyr et al., 2007;
 230 Hadi et al., 2018; Halliday et al., 2012; Jang and Lee, 2016; Mádai et al., 2015;
 231 Rentsenorov et al., 2018; Schöler et al., 2015; Yan et al., 2018; Záleská et al., 2018).

232
 233 Unfortunately, some of the researches are based on the use of SSA obtained in the laboratory
 234 (S Naamane et al., 2016; Dražen Vouk et al., 2017), while other use SSA which is taken from
 235 the SS incineration facilities (Chen and Poon, 2017; Kappel et al., 2017; Li et al., 2017; Piasta
 236 and Lukawska, 2016). Similar elements present in ash and dust obtained during technological
 237 scale incineration makes it impossible to compare with SSA incinerated in the laboratory
 238 furnace. It should be remembered that when SS is processed in incineration plants, it could be
 239 pre-stabilized by adding lime. The SSA obtained from lime-stabilized SS can be much more
 240 active than SSA prepared in the laboratory (Mejdi et al., 2020). Moreover, the technological
 241 processing of SS is different from the laboratory processing because some of the analytes are
 242 lost during the SS firing in the laboratory furnace (Tang et al., 2008; Youcai et al., 2004).

243 In addition, the laboratory production of SSA causes differences in the mineralogical
 244 composition, therefore, a sample of SSA produced on a simple, laboratory procedure is
 245 unrepresentative which may cause significant differences, e.g. instability or differences in
 246 durability, between cementitious materials containing technological or laboratory ash.

247

248 3. Sewage sludge ash in mortars as a partial binder or aggregate substitute

249 Sewage sludge ash can be treated as a substitute for the main binder or an additive in the
 250 mortar. The purpose of partial binder replacement is mainly to reduce its demand. The second
 251 type of research considered in the review paper is the use of SSA as an additive with and without
 252 removal of aggregate. Despite the differences in the description of the methodology itself, the
 253 presented approaches are similar. The average binder content based on the fresh weight of the
 254 mortar is 20% while SSA amounts 4.5% (Fig. 4). In general, partial substitution of the main
 255 binder or aggregate on SSA causes deterioration of mortar durability even after long curing
 256 time (Chang et al., 2010; Chen and Poon, 2017; Piasta and Lukawska, 2016). Table 1 presents
 257 the impact of SSA on the basic parameters of mortars with its addition. The deterioration of the
 258 strength properties is related to the lack of pozzolan reaction between the binder components
 259 as well as reduction of the total binder mass content in the mixture (Chen and Poon, 2017;
 260 Li et al., 2017; S Naamane et al., 2016).

261

262 Table 1. Characteristic of mortar samples containing SSA.

Type of cement	The share of SSA* [%]	Type of aggregate	W	S	WA	CS	Reference
OPC	2.9	Glass <5mm	↘	n.d.	↗	↘	(Li et al., 2017)
OPC	4.7	Sand + superplasticizer	↘	n.d.	n.d.	=	(Chen and Poon, 2017)
OPC	4.6	Sand	↘	n.d.	n.d.	↘	(Pan et al., 2003)
CEM I	4.6-6.9	Sand	↘	↗	n.d.	↘	(Chang et al., 2010)
OPC	3.3	Sand	↘	n.d.	n.d.	=	(Monzo et al., 1997)
OPC	4.7	Sand	n.d.	↗	n.d.	↘	(Mejdi et al., 2020)
CEM II/BL-32,5R	2.2 – 6.5	Sand	n.d.	n.d.	↗	↘	(Baeza-Brotons et al., 2014)
CEM II 42.5	2.2	Aggregate 0-4 mm	↘	↘	n.d.	=	(Dražen Vouk et al., 2017);



CEM III 32.5	4.4	Aggregate 0-4 mm + 5% metakaolin	↘	↘	n.d.	↗	(Dražen Vouk et al., 2017);
CP-IV-RS-32	7	Quartz sand	↘	n.d.	↘	↗	(Durante Ingunza et al., 2018);
CEM I 42.5 R	2.2	Quartz sand	n.d.	↗	n.d.	↘	(Piasta and Lukawska, 2016)
CEM I 42.5 R	5.1	Aggregate 0-2 mm	n.d.	n.d.	n.d.	=	(Záleská et al., 2018)
CEM I 52,5	6.7	Silica sand	↘	n.d.	n.d.	↘	(Alcocel et al., 2006)
CEM I 52,5R	5.6 -11.1	Quartz sand 0–2 mm	↘	↗	n.d.	↘	(Cyr et al., 2007)
CEM I 52,5N	2.2-6.7	Sand 0.516mm	↘	n.d.	↗	↘	(Krejcirikova et al., 2019)
CEM II/A-LL 52.5R	4.4	River sand 2-4mm	↘	n.d.	n.d.	=	(Kappel et al., 2017).

263

264 * - in a fresh state

265 W – workability

266 S – setting time

267 WA – water absorption of hardened samples

268 CS – compressive strength after 28-day of curing

269 ↘ – deterioration of the parameter relative to the control sample

270 ↗ – improvement of the parameter relative to the control sample

271 = - no significant change in the parameter relative to the control sample

272 n.d. – no data

273

274 Particles of SSA are characterized by considerable porosity causing the intensive water
 275 absorption. The amount of SSA in the mortar mixture is a factor determining its workability
 276 (Chang et al., 2010; Chen and Poon, 2017; S Naamane et al., 2016; Dražen Vouk et al., 2017).
 277 The problem related to the deterioration of workability can be solved by milling, thanks to
 278 which SSA particles become smoother, spherical-like and less porous (Chen et al., 2018;
 279 Kappel et al., 2017; Monzo et al., 1997; Pan et al., 2003; Rutkowska et al., 2018).

280 This phenomenon is called "lubricant effect" because the interlocking and friction between SSA
281 particles are reduced (Pan et al., 2003). It is worth noting that the improvement of mortar
282 workability by SSA milling is less significant compared to using a plasticizer
283 (Monzo et al., 1997). Milling also can change the colour of the mortar to slight red if SSA
284 contains significant amounts of Fe_2O_3 (Kappel et al., 2017). Colour change, as well as
285 significant shrinkage of the SSA-mortar during curing, may be limiting factors for its
286 application (Li et al., 2017). The problem of workability can also be mitigated by water/binder
287 (W / B) ratio reduction, but such solution can be used mainly for the production of prefabricates
288 or soil stabilization approaches and not of joint mortar.

289 The presence of SSA in the mortar also affects its setting time. It was observed that the
290 prolongation of the setting time is related to the amount of SSA in the mixture
291 (Chang et al., 2010; Mejdí et al., 2020; S Naamane et al., 2016; Piasta and Lukawska, 2016).
292 Extending the setting time (which is also longer compared to coal fly ash) is related to the
293 presence of phosphates in SSA. Formation of insoluble calcium phosphate limits the access of
294 water to the cement particles inhibiting the hydration reaction (Mejdí et al., 2020; Piasta and
295 Lukawska, 2016). Sewage sludge ash milling which is performed to reduce excessive water
296 absorption can also increase the setting time. The highly developed surface of SSA particles
297 absorbs calcium ions thus the hydration process is inhibited (Pan et al., 2003).

298 The use of SSA in mortar mixtures may also cause corrosion of the reinforcement due
299 to the high content of salts easily soluble in water. Alcocel et al. presented that the content of
300 chlorides and sulfates in SSA was 7.8 mg/g SSA and 37.2 mg/g SSA respectively. Of course,
301 the presented ratio will always strongly depend on the SS quality. However, it has been shown
302 that the SSA rinsing and subsequent drying process limits its negative effect on the corrosion
303 of reinforcement elements (Alcocel et al., 2006).

304 As mentioned, SSA obtained in the laboratory may show significant differences in both
305 the oxide and mineralogical composition. The improvement of binding properties of mortars
306 containing SSA with low CaO or amorphous phase content can be obtained by adding CaO to
307 the mixture in the form of e.g. lime or pozzolanic cement. It was shown that mortar based on
308 pozzolanic cement with the SSA addition (5.8% CaO in SSA mass) is water-tight, and thus
309 capillary water absorption decreases with the share of SSA in the hardened mixture.
310 The increase in mortar density, as well as the filling of free spaces between aggregate particles,
311 improves mortar resistance to water and its mechanical properties. It was observed that samples
312 containing 7% of SSA (in total fresh mortar mass) have 39% higher compressive strength in
313 comparison to the control sample (Durante Ingunza et al., 2018).

314 The mechanical properties of the mortars based on ordinary Portland cement even with
315 a 5% addition of SSA with moderate CaO content (up to 20%) and a high proportion of the
316 active amorphous phase did not differ significantly from the control samples. During mortar
317 curing, the content of portlandite is reduced, but the pozzolanic reaction is not a factor
318 conditioning the final properties of the material (Záleská et al., 2018). A slight decrease in the
319 compressive strength of the mortar sample in relation to the control sample can be observed
320 when SSA constitutes a greater proportion in the binder. Mejdí et al. reported that after 28 days
321 of curing mortar with 20% cement replacement to SSA (containing 20,1% CaO) compressive
322 strength of SSA-mortar was reduced by approximately 9% in comparison to control sample
323 (Mejdí et al., 2020). Similar observations were made for mortar with high CaO content
324 (31.3 – 52.2%), based on ordinary Portland cement. The presence of SSA in the mixture does
325 not significantly reduce the compressive strength of mortars comparing to control samples.
326 The use of SSA with high CaO content and maintaining an appropriate W / B ratio (0.5) by
327 using plasticizer means that the mechanical properties of mortars are similar to reference
328 samples, therefore there is no need for additional mineral materials or binders to improve
329 mechanical properties (Monzo et al., 1997; Dražen Vouk et al., 2017).

330 Another solution to reduce the negative impact of SSA on the mechanical properties of
331 mortars is the use of mineral additives (metakaolin, nano-silica) or multi-component cement.
332 Nano-silica increases hydrates nucleation and crystal growth as well as accelerate the hydration
333 reaction, which can improve the negative effects caused by SSA addition to mortars
334 (Lin et al., 2008). Satisfactory strength properties are also obtained using multicomponent
335 binders (e.g. CEM II, CEM III). These types of binders enhance the occurring pozzolan reaction
336 thus obtained mortars are characterized by good mechanical properties
337 (Baeza-Brotons et al., 2014; Kappel et al., 2017). Garcés et al. indicate that cement CEM II /
338 B-M (V-LL) 42.5R is the most suitable binder for mortars containing SSA (Garcés et al., 2008),
339 however, the use of additives or special cement must be preceded by an analysis of the SSA
340 composition, because such solutions may not always be effective.

341 Replacing the main binder in mortars is usually limited to a small share of SSA.
342 The production of mortars based on high-strength cement is an interesting solution. Despite the
343 use of washed SSA (to remove corrosive ions), it was shown that with increased W / B ratio
344 (0.7) and 60% cement (CEM I 52.5) replacement, a material with a compression strength of
345 13.0 MPa was obtained. Therefore the management of significant amounts of SSA is
346 economically and environmentally justified and the resulting material could be used in
347 construction (Alcocel et al., 2006). The use of SSA with a moderate CaO content, without prior



348 removal of corrosive ions, as well as maintaining an appropriate W / B ratio results in a material
349 with satisfactory mechanical properties. Despite the deterioration of strength in the early
350 hardening phase, the mortar based on high-strength cement (CEM I 52.5) with 50 % binder
351 substitution has a strength of only 16 % lower than the reference sample. However, it should
352 be remembered that the final compressive strength of the mortar is not limited only to the use
353 of high-class cement. Krejcirikova et al. presented research on the replacement of lime cement
354 with SSA from two different SS incineration plants. Despite the use of SSA's with medium
355 CaO content (23.4 and 36.4%) and high strength class cement, a significant decrease in strength
356 was recorded with a 10% binder replacement (aprox. 25 and 20% respectively). It can be
357 assumed that the SiO₂ / Al₂O₃ ratio in both SSA's was high, therefore the deterioration of the
358 compressive strength was mainly caused by the dilution effect and more porous structure
359 formation (Krejcirikova et al., 2019).

360 As mentioned before, the hydrated structure of mortar or concrete can immobilize heavy
361 metal cations (Záleská et al., 2018). It has been proven that the binding ability of Pb²⁺ ions is
362 connected with the content of SSA in the mortar. A high proportion of SSA in the mortar results
363 in the reduction of the concentration of Pb²⁺ ions in the leachate after washing the hardened
364 samples (Li and Poon, 2017). The effect of immobilizing heavy metal ions in a hydrated cement
365 matrix is related to the highly developed specific surface area, the porosity of the hardened
366 material and the ion exchange effect induced by SSA particles. It has been observed that
367 phosphates from SSA react with Pb²⁺ ions from the contaminated aggregate. The reaction
368 product of both mentioned substrates is a crystalline lead phosphate (Li et al., 2017).

369 Most of the research on leaching heavy metals from hardened products are based on rinsing
370 monolithic hardened mortar samples. In the case of crushed samples, it is obvious that the
371 leachability of heavy metals is greater due to the larger contact surface. It has been reported that
372 the increase in heavy metal concentration in crushed samples increased from 3 to 6 times
373 compared to reference samples. However, the leaching behaviour of samples with SSA was of
374 the same order of magnitude as the reference samples without residue (Cyr et al., 2007). It was
375 shown that 25 % replacement of cement (CEM I 52,5 R) for SSA resulted in a 15 % reduction
376 in the total mortar soluble fraction. The incorporation of SSA in mortar did increase the average
377 concentration of heavy metals, but this difference in relation to the control sample is not
378 statistically significant. Based on the analysis of the results, it was determined that the metal
379 concentrations in the leachate: Ti, V, Cr, Ni, Cu, Zn, As, Cd, Sn, Sb and Pb meet the
380 requirements for drinking water quality presented by the World Health Organization (WHO)



381 (Coutand et al., 2006). However, it is important to perform other elements leaching analysis to
382 prove full environmental safety of such an approach.

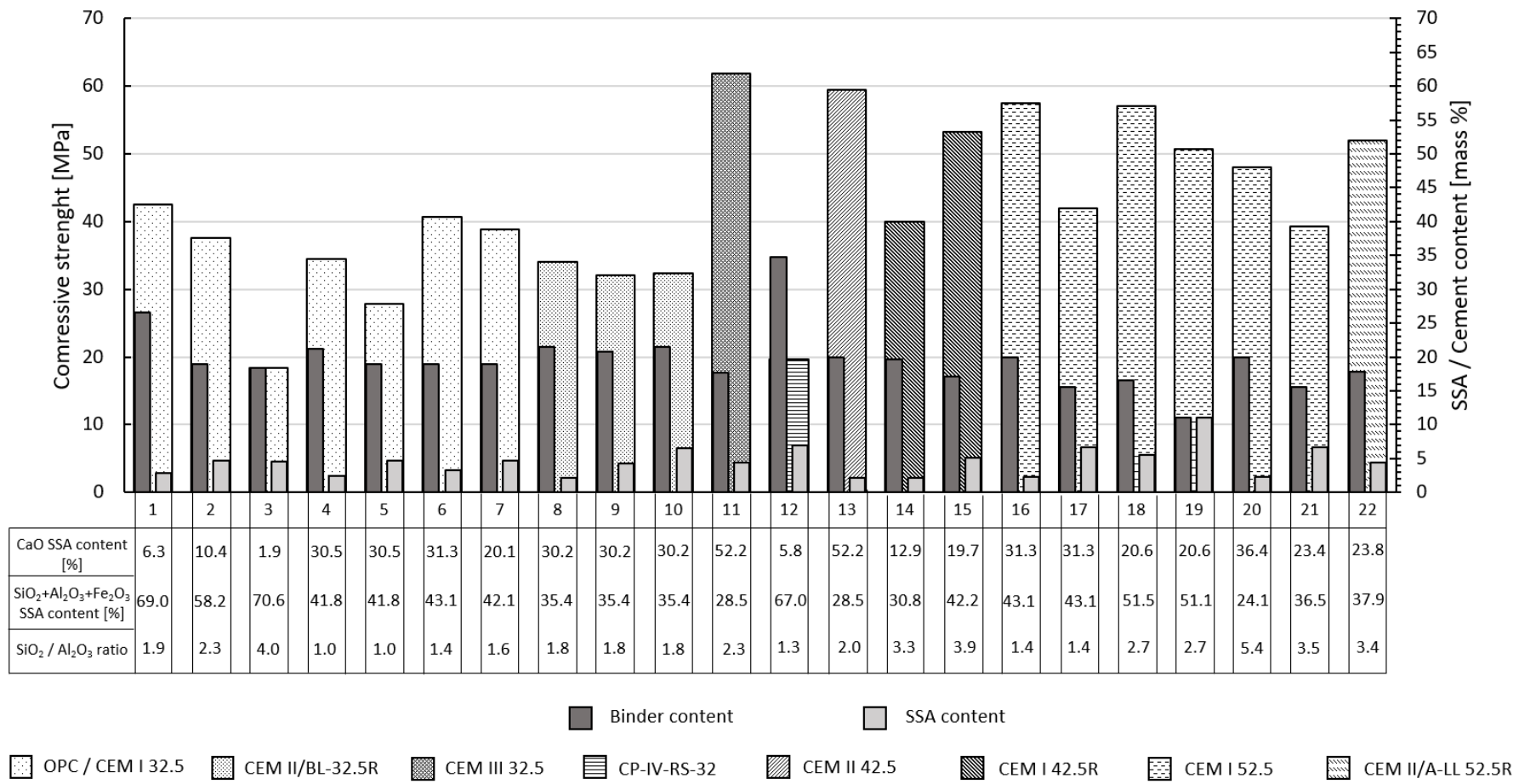


Figure 4. Compressive strength and shares of binders and SSA in mortars based on various cement binders after 28 days of curing. 1 - (Li et al., 2017); 2- (Chen and Poon, 2017); 3 - (Pan et al., 2003); 4, 5 - (Chang et al., 2010); 6 - (Monzo et al., 1997); 7 - (Mejdi et al., 2020); 8, 9, 10 - (Baeza-Brotons et al., 2014); 11, 13 - (Dražen Vouk et al., 2017); 12 - (Durante Ingunza et al., 2018); 14 - (Piasta and Lukawska, 2016); 15 - (Záleská et al., 2018); 16, 17 - (Alcocel et al., 2006); 18, 19 - (Cyr et al., 2007); 20, 21 - (Krejcirikova et al., 2019); 22 - (Kappel et al., 2017).

349 Figure 4. shows the compressive strength of mortar samples in which SSA is present.
350 Due to the diversity in the designed research, the Figure also shows the share of the binder as
351 well as its type. To estimate the impact of SSA quality on the mechanical properties of mortars,
352 the sum content of pozzolanic oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$), the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio as well as
353 the percentage content of CaO in SSA was also presented.

354 Based on the analysis of the data presented in Figure 4 it can be concluded that the
355 quality of SSA has a significant impact on the mortars mechanical properties. When using
356 Ordinary Portland Cement (OPC) and SSA with a low CaO content and high $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio
357 (despite the high content of pozzolanic oxides), a material with low compressive strength was
358 obtained (Chen and Poon, 2017; Li et al., 2017; Pan et al., 2003) despite the significant
359 proportion of main binder (samples 1-3). In the case of using SSA with a moderate amount of
360 CaO (approx. 20-30%) the mechanical properties of OPC-based mortars depend on the share
361 of SSA and the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio (samples 4-6) (Chang et al., 2010; Mejdí et al., 2020;
362 Monzo et al., 1997). The deterioration of the mechanical properties of mortars may also be
363 associated with the dilution effect, especially in the case of substitution of the main binder or
364 SSA addition to the mixture without partial aggregate removing.

365 Pozzolanic cement as a source of CaO has a positive effect on the properties of mortars
366 containing SSA. Durante Ingunza et al. presented that mortar compressive strength containing
367 7 % SSA was 24.7 % higher. Compared to the data presented in the Figure 4, mortar based on
368 pozzolanic cement (sample 12) may seem unsuitable for this type of management methods,
369 however, it obtains satisfying mechanical properties after longer curing time.

370 Mortars based on CEM II / BL-32.5R cement do not show significant loss of mechanical
371 properties, even when significant amounts of SSA (over 5 %) are included in the mortar mass,
372 which confirms the suitability of use multi-component cement as binders (samples 8-10)
373 (Baeza-Brotons et al., 2014; Garcés et al., 2008).

374 As mentioned, the high content of CaO in the used SSA does not cause a significant loss
375 of strength properties of the samples. The effect is more visible if the $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio is
376 similar to the fly ash oxides ratio (approx. 2.4) (Fernández-Jiménez and Palomo, 2005; Jang
377 and Lee, 2016; Richardson et al., 2016; Suksiripattanapong et al., 2015). Despite the low
378 content of pozzolanic oxides in SSA and the different binders used (samples 11 and 13),
379 satisfactory mechanical properties were obtained.

380 Based on the results presented by Piasta and Lukawska and Záleská et al. (samples 14
381 and 15) the addition of SSA with high $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio did not show a significant effect on
382 the properties of the sample. The SSA used in the research can be treated more like a fine



383 aggregate and not as an active mineral material (Piasta and Lukawska, 2016;
384 Záleská et al., 2018).

385 In mortars based on high-strength cement (e.g. CEM I 52.5, CEM II 52.5), the SSA
386 quality has the greatest impact on their properties, i.e. the amount of active oxides and their
387 ratio (samples 16-22). The use of SSA with a moderate amount of CaO and ratio of oxides
388 similar to coal fly ash allows to the incorporation of significant amounts of SSA (over 10 %)
389 without significant loss of mechanical properties which in the context of waste management is
390 the most appropriate solution.

391

392 **4. Sewage sludge ash in concretes as a partial binder or fine aggregate substitute**

393 Concrete is the second most commonly used material in construction after mortar.
394 Research on the impact of SSA on concretes involves: main binder substitution, direct addition
395 of SSA without removing the fine aggregate and partial replacement of the fine aggregate.
396 The presence of SSA in concrete as well as in mortar reduces its durability (Chen et al., 2018;
397 Fontes et al., 2016; Halliday et al., 2012). The SSA concrete strength loss is mainly proportional
398 to SSA content (Jamshidi et al., 2013). Deterioration of mechanical properties is observed when
399 SSA with a low CaO or amorphous phases content is introduced into the OPC concrete mixture
400 (Fontes et al., 2016). It has been shown that substitution of 10 % of the main binder for SSA
401 resulted in a slight deterioration of strength (4-8 %) compared to the control. Further increasing
402 the SSA share (20 %) results in a 23-29 % strength reduction (Halliday et al., 2012).
403 As presented by Lu et al. replacing the binder in 20% causes the binder dilution effect, therefore
404 the compressive strength of the SSA concrete was lower than that of the control sample
405 (Lu et al., 2019). It is worth adding that the introducing of significant amounts of SSA is
406 associated with a significant loss of workability of the mix, therefore achieving homogeneity
407 of concrete may become difficult (Halliday et al., 2012; Rutkowska et al., 2020). Changes in
408 the basic parameters caused by the presence of SSA in the concrete mix are presented in
409 Table 2.

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417 Table 2. Characteristic of concrete samples containing SSA.

Type of cement	The share of SSA* [%]	Type of aggregate	W	S	WA	CS	Reference
OPC	2.3-4.6	Granite <5mm	n.d.	n.d.	↗	↘	(Chen et al., 2018)
CEM I	1.5-4.5	Fine + 10 mm + 20 mm aggregate	n.d.	n.d.	n.d.	↘	(Halliday et al., 2012)
OPC	1.8	Sand + gravel	n.d.	n.d.	n.d.	=	(Barbosa and Filho, 2004)
CEM I 32,5	0.7-2.2	Natural aggregate 0.125-16 mm	n.d.	n.d.	n.d.	=	(Rutkowska et al., 2018)
CEM I 32,5	0.8-3.9	Natural aggregate 0.125-16 mm	n.d.	n.d.	n.d.	=	(Rutkowska et al., 2020)
CEM II	1.6	Gravel and sand	n.d.	n.d.	=	↘	(Jamshidi et al., 2012)
CP II F-32	1.2	River sand 2.8 mm + granite gravel 9.5 mm	n.d.	n.d.	↘	↘	(Fontes et al., 2016)
PC 32	2.9	Quartz sand + granite gravel	↘	n.d.	↘	↗	(Lima et al., 2015)
CEM I 42,5N – HSR/NA	7.9-15.8	Sand 0/2, natural aggregate 2/4 and 4/8	n.d.	n.d.	=	↘	(K.Kazberuk, 2011)
CEM II BM (S-LL)-42.5R	0.6-1.2	F-0/4 and F-2/8 aggregates	n.d.	n.d.	↘	↘	(Baeza-Brotons et al., 2014).
CEM II BM (S-LL)-42.5R	6.0	F-0/4 and F-2/8 aggregates	n.d.	n.d.	↘	↗	(Baeza-Brotons et al., 2014).
CEM I 52,5	1,7	Natural aggregate 5-10 mm, recycled aggregates waste glass aggregate 0-5mm	n.d.	n.d.	n.d.	↘	(Lu et al., 2019)

-
- 418 * - in a fresh state
419 W – workability
420 S – setting time
421 WA – water absorption of hardened samples
422 CS – compressive strength after 28-day of curing
423 ∨ – deterioration of the parameter relative to the control sample
424 ↗ – improvement of the parameter relative to the control sample
425 = - no significant change in the parameter relative to the control sample
426 n.d. – no data

427 The presence of amorphous phase in SSA may enhance pozzolanic reaction in the later
428 stages of concrete hardening, but mainly high CaO content and active oxide ratio in SSA
429 intensify this reaction (Halliday et al., 2012). As the curing time increases, the compressive
430 strength of the concrete sample increases, however, this increase is also observed for the control
431 sample without the addition of SSA. By extending the curing time sufficiently long, the
432 differences between the durability of SSA concrete and the control samples are insignificant
433 (Rutkowska et al., 2020). This phenomenon can be related to the slight pozzolanic activity of
434 SSA. Moreover, the SSA particles constituting additional nucleation sites during cement
435 hydration (Jamshidi et al., 2012).

436 Sewage sludge ash obtained in an incineration plant with high CaO content can be
437 successfully used as a partial binder substitute in concretes. It was shown that replacing 10 %
438 of cement with SSA resulted in a 25 % improvement in compressive strength compared to
439 control samples. It is possible that such products can be used in construction because their
440 properties, e.g. strength, thermal conductivity or water resistance meet the requirements
441 (e.g. EN 771-3 standard) (Pérez-Carrión et al., 2014).

442 The use of CaO-rich SSA, even if it is produced in a laboratory, as a partial replacement
443 of fine aggregate increases the density of concrete, which results in increased strength. It has
444 been observed that compressive strength of the concrete in which a part of the fine aggregate
445 was replaced with SSA (30 % CaO) is twice higher than the samples in which the aggregate
446 was not removed in favour of SSA (Baeza-Brotons et al., 2014). Rutkowska et al. reported that
447 SSA containing a moderate amount of CaO (about 20%) can positively affect concrete
448 properties. After 28 days of hardening of the concrete sample with the 20% SSA replacement,
449 the compressive strength increased by 2.9% compared to the control (Rutkowska et al., 2020).



450 The influence of SSA on the strength properties of concrete is probably caused by the
451 pozzolanic reaction, since the substances contained in SSA and cement together may constitute
452 a binder, which total amount is significantly higher. The problem associated with low CaO
453 content in SSA can be solved by using pozzolanic cement to concrete preparation. It was found
454 that the 3% SSA (6.2% CaO) addition (in total fresh concrete mass) without aggregate removal
455 to concrete based on pozzolanic cement caused the hardened samples to be almost twice as
456 durable as the control sample (Lima et al., 2015). Alternatively, CaO content can be increased
457 directly in SSA, as mentioned before in section related to the SSA mortar quality.

458 The improvement of the mechanical properties of concretes is mostly observed in the
459 case of a small proportion of SSA in the total mass of the cement mixture. Further increasing
460 the content of SSA in the mixture results in high water demand during preparation and
461 significant shrinkage of the products during curing (Chen and Poon, 2017; Rutkowska et al.,
462 2018). Increasing the W / B ratio to improve the workability of the fresh concretes causes
463 reduction in durability properties due to the formation of a more porous matrix. The use of
464 plasticizer as well as milling or changing the W / B ratio is a good solution for the elimination
465 of high SSA water absorption (Fontes et al., 2016; Halliday et al., 2012; Lima et al., 2015;
466 Rutkowska et al., 2020, 2018). Ensuring homogeneity and water access to the binder particles
467 does not significantly reduce the mechanical properties of SSA concrete (Jamshidi et al., 2013).
468 It is worth adding that the SSA can increase concrete porosity, despite maintaining the
469 appropriate W / B ratio and using a plasticizer. It has been shown that the porosity of concrete
470 increases with the proportion of SSA in the mix, especially when low active SSA is used
471 (Lu et al., 2019), however, the pores in the matrix are closed. The improvement of water-
472 tightness makes concrete more durable because it is more resistant to aggressive environments
473 and frost (Baeza-Brotons et al., 2014; Barbosa and Filho, 2004). Moreover, SSA used as an
474 admixture in concrete prefabricated/blocks, cause the thermal conductivity decrease due to
475 reduced mix porosity and compactness (Lu et al., 2019).

476 The binding capacity of heavy metals by SSA is also confirmed with respect to the
477 Commission Decision of 18 December 2014 (2014/955/EU) on the list of waste concerning,
478 inter alia, the leaching of heavy metals from waste (Commission Decision of 18 December,
479 2014). For concrete in which cement was substituted with SSA in an amount of 15%, the sum
480 content of elements in the leachate (Cd, Cr, Cu, Ni, Pb, Zn, As, Sb, Se, Ba, Hg, Mo)
481 was 1.2 mg/L. A similar observation was recorded for 25% cement substitution, where the sum
482 of mentioned leached heavy metals was 1.5 mg/L. In accordance with Commission Decision,
483 the maximum concentration of each mentioned element in leachates cannot exceed 10 mg/l



484 (Cieślik et al., 2018; Rutkowska et al., 2020, 2018). K.Kazberuk presented that replacing 25%
485 of the binder in concrete for SSA, in addition to obtaining satisfactory strength properties,
486 concrete can be regarded as safe and does not cause any environmental risk
487 (K.Kazberuk, 2011). Based on heavy metal leaching tests (Toxicity Characteristic Leaching
488 Procedure (TCLP Method 1311, 1992)) it was confirmed that the leachability of heavy metals
489 from SSA-containing concrete was lower than in the case of coal fly ash-containing ones
490 (Chen et al., 2018).

491 Figure 5. presents the compressive strength of concrete samples in which SSA is present
492 as well as CaO content, the sum of active oxides and its ratio. Despite the high share of
493 pozzolanic oxides and similar $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio to coal fly ash, the mechanical properties of
494 concretes (labelled as 1 and 2) are mostly determined by the share of binder and SSA, which in
495 this case exhibits pozzolanic properties (Chen et al., 2018). Increasing active SSA content in
496 concrete causes slight decrease in compressive strength, while lower $\text{SiO}_2 / \text{Al}_2\text{O}_3$ ratio in SSA
497 causes more drastic strength loss with the increase of SSA's share (Halliday et al., 2012).
498 The moderate content of CaO in SSA (about 20 %) may also contribute to the fact that the
499 decrease in strength is less intense with the increasing share of SSA in concrete
500 (samples 6, 7, 8).

501 Due to the limited data on the effect of SSA on CEM II-based concrete, its impact is
502 difficult to determine. Considering the differences in SSA's composition (samples 9, 10), it can
503 be assumed that the share of the main binder has the greatest impact on the concrete mechanical
504 properties. Sewage sludge ash consisting mostly of SiO_2 has poor binding properties thus the
505 decrease in strength is associated with a decrease in the overall binder content.

506 The results presented by Lima et al. where the concrete was based on pozzolanic cement,
507 confirm that the external addition of CaO positively affects the SSA-concretes strength. It was
508 shown that after 28 days of curing, in concrete with 10 % (in relation to the weight of cement)
509 addition of SSA, the strength value improved by 44 % (Lima et al., 2015).

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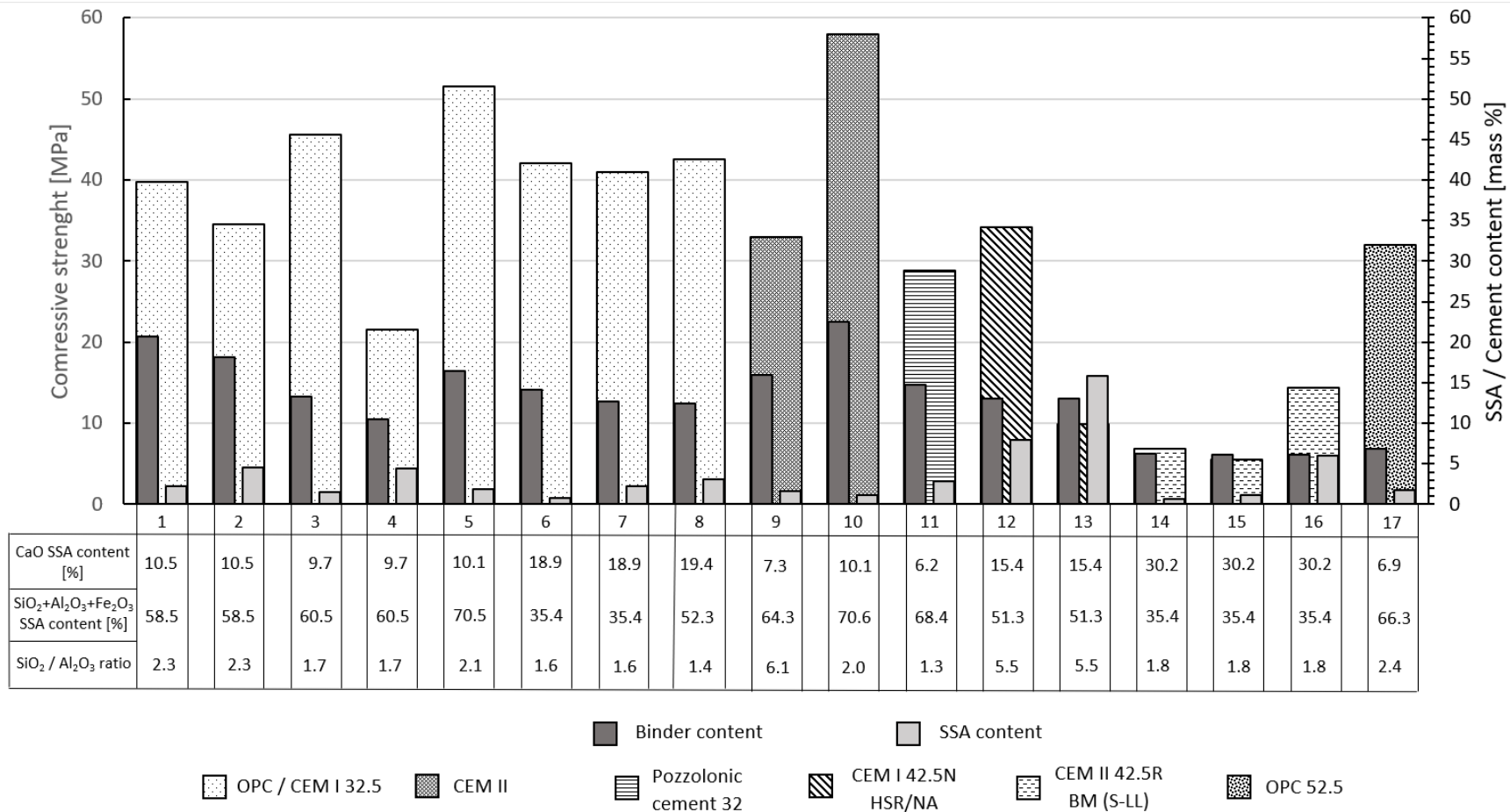


Figure 5. Compressive strength and shares of binders and SSA in concretes based on various cement binders after 28 days of curing.

1, 2 - (Chen et al., 2018); 3, 4 - (Halliday et al., 2012); 5 - (Barbosa and Filho, 2004); 6, 7 - (Rutkowska et al., 2018); 8 - (Rutkowska et al., 2020); 9 - (Jamshidi et al., 2012); 10 - (Fontes et al., 2016); 11 - (Lima et al., 2015); 12, 13 - (K.Kazberuk, 2011); 14, 15, 16 - (Baeza-Brotos et al., 2014); 17 - (Lu et al., 2019).

503 The use of special binders (bridge and airport cement) in concrete with the addition of
504 low-active SSA (samples 12 and 13) results in a drastic decrease in strength during the
505 increasing share of SSA. It is worth noting that the values shown in Figure 5 relate to
506 compressive strength after 28 days of curing. K.Kazberuk presented that after 180 days of
507 curing, the samples are characterized by about twice as high strength as those after 28 days of
508 curing (K.Kazberuk, 2011).

509 The test results labelled as 14-17 concern the use of SSA in concrete intended for the
510 production of prefabricated elements. The nearly double increase in concrete strength may be
511 associated with the pozzolanic reaction between SSA components and multi-component
512 cement, causing secondary hydration phases formation, however, the increased density and
513 filling the free spaces between aggregate particles by SSA was the decisive effect on final
514 mechanical properties (Baeza-Brotons et al., 2014). Lu et al. indicate that such products do not
515 require high durability, and therefore other waste materials can be included in the concrete
516 mixture. In addition, production of partition blocks is a novel and eco-friendly approach for
517 SSA utilization. (Lu et al., 2019).

518 It is worth mentioning that difficulty in estimating the impact of SSA on the
519 physicochemical properties of hardened concretes is the variety of used aggregates. Stiffness
520 and compressive strength of concrete depend also on the aggregate type as well as its particle
521 size, therefore, differences between mechanical properties may occur (Ćosić et al., 2015).

522

523 **5. Conclusions**

524 Due to the increase in the popularity of SS thermal utilization methods, more and more
525 ecological concepts of using SSA are being created. As a result of some similarities of SSA to
526 coal fly ash, commonly used in the construction industry, SSA can be utilized in mortars or
527 concretes mixtures. In such products, this waste is treated as an active pozzolanic additive or
528 the main binder substitute. One of the greatest limitations of using SSA in cementitious building
529 materials is the fact that SS from different incineration facilities may differ significantly.
530 Regardless of the method of SS incineration, obtained SSA should always be treated as a
531 material similar in properties to fine aggregate rather than a binder. Due to very diverse
532 characteristics of SS, and its processing methods, SSA obtained from different sources should
533 be thoroughly characterized separately before implementing the most appropriate utilization
534 method. Moreover, the problem of the significant differences in the characteristics of SSA
535 obtained at laboratory scale and SSA obtained at technical scale is crucial for developing of
536 suitable waste management approach. Any strong statements regarding the possibilities of using



503 SSA in the construction industry should be supported by at least SSA incineration industrial-
504 scale trials.

505 Based on the analysis of the results collected in this article, it could be stated that SSA,
506 as a mineral component, has a negative impact on almost all mortar or concrete materials
507 parameters. The activity of SSA in cement-based products depends mainly on its oxide and
508 mineralogical composition as well as the type of used binder. The deterioration of mechanical
509 properties is observed when low-active SSA even in small amounts is used. However, the
510 negative impact of the presence of SSA on cement mixtures can be reduced by modifying the
511 ratio of active oxides. The high share of CaO and pozzolanic oxides (SiO_2 , Fe_2O_3 , Al_2O_3) in
512 SSA may contribute to the pozzolanic reaction in a cementitious mixture based on OPC, thus
513 compressive strength decrease is smaller. The discussed problem can be omitted at the stage of
514 SS incineration. Addition of Ca, Si, Fe and Al species to SS is a trivial approach which could
515 be an effective solution for the implementation of new waste management approach directly in
516 the sewage sludge treatment plant or in the incineration facility. On the other hand, the use of
517 low CaO content SSA could be more suitable when specific binders (e.g. multi-component
518 cement) or additional source of CaO (lime or pozzolanic cement) are used. It is worth noting
519 that the smallest parameters deterioration of SSA-containing samples is observed when high-
520 strength binders (e.g. CEM I 52.5 or CEM II 52.5) are used. It is especially important in case
521 of planning a possible increase of CaO content in SSA by simple technological operations at
522 the stages of wastewater treatment or SS incineration.

523 The presence of SSA in cement mixtures, in addition to the deterioration of the
524 mechanical characteristics, is also often associated with deterioration of workability,
525 prolongation of setting time and product shrinkage. Worse workability parameter can be
526 compensated by changing the W / B ratio, milling SSA or using a plasticizer. However,
527 SSA milling can cause significant shrinkage of products during curing, while an increase in the
528 W / B ratio is associated with an increase in porosity. The use of plasticizer is the most suitable,
529 however, it can generate additional costs, especially when SSA constitutes a significant share
530 in the product.

531 The last parameter determining both, durability and environmental safety of mortar and
532 concrete is water absorption by cured samples. In the case of mortars, an increase in the water
533 absorption capacity is observed while the concrete becomes more watertight. Therefore, the use
534 of SSA in building materials should be limited mainly to applications in concrete mixtures.

535 It is also important to mention that the main advantage of incorporating SSA into building
536 materials is the fact that the toxic heavy metals present in SSA are safely immobilized, and



503 therefore do not pose a risk to the environment. Moreover, it gives the opportunity to minimize
504 the amount of unmanaged solid residues production for many sewage sludge treatment plants.
505 It must be kept in mind that strength, workability, setting time or water absorption are not the
506 only ones of the characteristic features that are affected by the presence of SSA in the cement
507 mixture. For a detailed assessment, other aspects, such as environmental safety or other
508 mechanical properties, should also be considered. Before considering any technological scale
509 application, the laboratory-scale test should always be supported by data obtained during
510 industrial-scale trials.

511 Despite the many negative aspects associated with the use of SSA in building materials,
512 it is possible to reduce them by simple solutions but there is an urgent need for further research
513 to optimize existing ones.

514

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517 commercial, or not-for-profit sectors.

518

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