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6

7 **Title: *The potential of raw sewage sludge in construction industry – a review.***

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13

14 **1. Abstract**

15 Excess sewage sludge produced in any municipal or industrial wastewater treatment plant
16 becomes a serious problem due to its increasing amount. This increase is related to the
17 improvement of treatment technologies, expansion of sewage systems and the development of
18 new industrial plants. The implementation and development of new technologies related to the
19 utilization of sewage sludge is currently based on treating it as a substrate. Construction is an
20 industry branch where sewage sludge, as well as other waste materials, can be used. The use of
21 sewage sludge in building materials eliminates some of the expensive and energy-intensive
22 stages of utilization, and the final product obtained is often stable and safe. This is confirmed,
23 among other research regarding strength properties, water resistance, frost resistance and heavy
24 metal leaching, especially when the amount of sewage sludge in solidified samples is low. The
25 main purpose of the article is to present the latest methods of using sewage sludge (dried,
26 dehydrated, and raw) in building and construction materials. Methods of producing low-
27 strength materials for landfilling purposes have also been described.

28 The stabilization of sewage sludge with binding additives improves the end product's
29 durability compared to standard solutions (dewatering). The use of sludge in concrete and
30 mortars mixes is usually associated with a reduction in their strength compared to mixtures
31 without sludge. The binder in the mixture is responsible for the strength of concrete or mortar.
32 Sintering sewage sludge to make ceramic products (bricks, tiles) and lightweight aggregates is
33 a promising approach, but in comparison to other methods such solutions require more energy

34 expenditure. Nevertheless, the obtained products are stable and their durability, while lower
35 than that of the control samples, still qualifies them for applications in construction.

36 Due to the different physicochemical properties of sludge, the methods of its management
37 should be designed separately. It is therefore difficult to select one general and the most optimal
38 method of management of sludge in building materials, but on the basis of the presented review,
39 the authors indicate that one of the best methods of management is sintering sewage sludge into
40 lightweight aggregates.

41 **1. Introduction**

42 The increasing amount of produced waste and the increasing emphasis on acting in
43 accordance with sustainable development means that research is conducted on new waste
44 management concepts which use waste from various industries as raw materials (Lynn et al.,
45 2016). Wastewater treatment plants are one of the sources of nuisance waste. A significant
46 amount of sludge is obtained there by mechanical and biological wastewater treatment, which
47 includes microorganisms and potentially harmful organic and inorganic substances. Such
48 a sediment is known as excess sludge (Peccia and Westerhoff, 2015). The management of
49 excess sewage sludge produced in any municipal or industrial wastewater treatment plant
50 becomes a serious problem due to its increasing amount and a possible negative impact on the
51 environment and people. In the years 1992-2005 in the countries of the so-called "old EU" the
52 introduction of restrictions on municipal wastewater treatment led to as much as a 50 % increase
53 in the total amount of produced sludge. In those countries, in 2010/2011, a 20 % increase in
54 sludge production was observed (a total increase of 10.4 million tonnes dry matter (DM) of
55 sludge). In contrast, in such countries as Bulgaria, the Czech Republic, Estonia, Lithuania,
56 Latvia, Malta, Poland, Romania, Slovakia, Slovenia, Cyprus and Hungary, the increase in
57 production was 100 % (2.5 million tonnes DM of sludge in total). The difference in the annual
58 production of sludge in those countries results from different levels of implementation of the
59 directives concerning wastewater treatment and sludge management (Collivignarelli et al.,
60 2017; Grobelak et al., 2016; Pellegrini et al., 2016; Środa et al., 2013). It is estimated that the
61 amount of the produced sewage sludge in Europe in 2020 will amount to 13 million tonnes DM
62 of sludge, which gives approx. 45-56 g dry matter of sludge per capita per day (Mininni et al.,
63 2015).

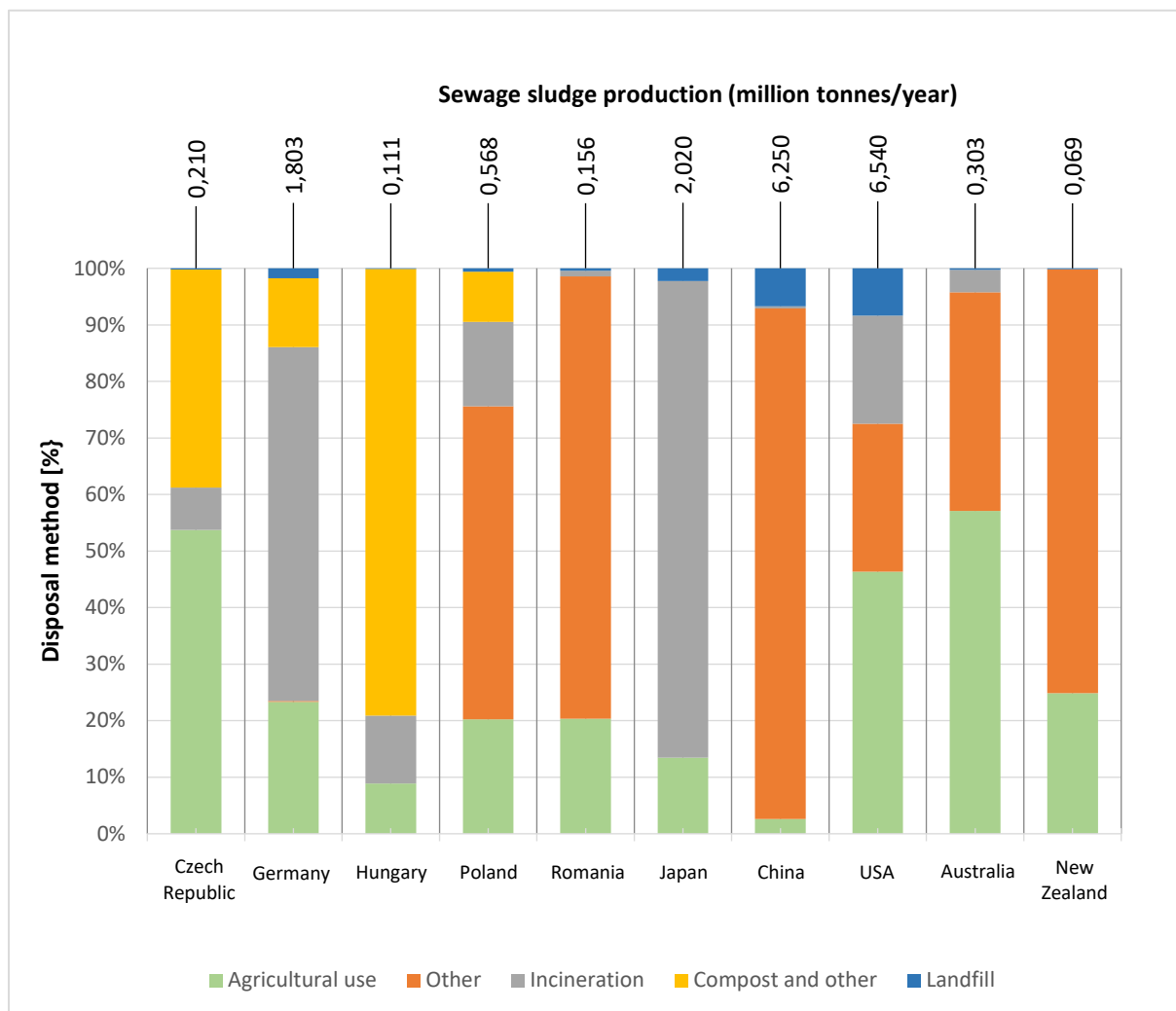
64 Sewage sludge management is a problem not only in European countries. It also applies to
65 Asian countries. In Japan, from 1990 to 2004, an increase in the production of sewage sludge
66 was observed by as much as 170 %. Currently, more than 2.2 million tonnes of dry matter of



67 sediments is produced in Japan (Hong et al., 2009). This country, considered as one of the most
68 developed, uses a number of methods for the management of sewage sludge or biosolids based
69 on the recovery of energy from them (Christodoulou and Stamatelatou, 2016). Also in China,
70 since 2007 to 2013 a rapid increase in the production of sewage sludge has been recorded,
71 which was associated with the sudden development of sewage sludge treatment plants. In 2013,
72 6.25 million tonnes of DM of sewage sludge was produced in China. The amount of sludge per
73 capita is much lower than in developed countries, but it is probably related to the differ,
74 sometimes outdated, sewage sludge management methods and the size of the population (Yang
75 et al., 2015). In the case of Australia, low population density and relatively small production of
76 sewage sludge (about 303000 tons of DM biosolids per year) means that their management is
77 subject to much public scrutiny (Pritchard et al., 2010). In less developed countries,
78 for e.g. countries of Africa, Asia or Latin America, the number of wastewater treatment plants
79 is considered small (per capita). As a result, the utilization of sewage sludge or biosolids is
80 minimal or not carried out at all. In addition, in many countries, there are no regulations
81 regarding sewage sludge management, which is why sewage from septic tanks goes to water
82 bodies or direct into soil, which has a negative impact on the environment and public health.
83 (Drechsel et al., 2015)

84 EU Member States are obliged to implement Council Directive 86/278 / EEC of 12 June
85 1986, where main rules regarding the use of sewage sludge for agricultural purposes are
86 defined. Some countries, in addition to the implementation of the directive, impose additional,
87 more stringent requirements for the quality of excess sewage sludge, thus its management poses
88 more and more problems for owners and operators of sewage treatment plants.

89 There is a tendency to renounce conventional solutions due to a gradual decrease in the
90 "capacity" of landfills and prohibitions on sewage sludge storage in EU countries. In addition,
91 more emphasis is put on the quality of sewage sludge and composts produced from it, which
92 have to be controlled in terms of, among other things, content of heavy metals and pathogens.
93 In many European countries sewage sludge does not meet the current regulations regarding
94 their quality, which is why it cannot be used in agriculture or stored, and its combustion can
95 only take place in modern incineration plants (Mininni et al., 2015).



97

98 Figure 1. Worldwide implemented excess sewage sludge utilization methods (Christodoulou and Stamatelatu,

99 2016; Drechsel et al., 2015; Eurostat, 2015; Yang et al., 2015)

100 One of the industries in which waste materials can be used is the construction industry,

101 which plays a significant role both in developing and developed countries. Pro-environmental

102 action and sustainable construction practices, as well as an increasing demand for cement, are

103 the factors which contribute to the use of waste materials in this industry, coming from

104 construction and other industries, e.g. ashes from biomass incineration, blast furnace slag,

105 gangue, sewage sludge and ashes after its thermal utilization, waste glass or materials after

106 demolition of buildings (Smol et al., 2015; Supino et al., 2016). The use of sewage sludge in

107 mortars or construction materials eliminates some of the expensive and energy-intensive stages

108 of their disposal. In addition, environmentally harmful waste is transformed into a safe and

109 stable product. The use of sewage sludge in mortars or construction materials eliminates some

110 of the expensive and energy-intensive stages of its disposal. In addition, environmentally
111 harmful waste is transformed into a safe and stable product.

112 The addition of excess sludge in raw form to the production of cement and mortar
113 products may be an alternative to the existing methods of its management (Paris et al., 2015),
114 its presence, however, may adversely affect the durability of manufactured products. This is
115 mainly caused by the content of organic substances and heavy metals, which slow down and
116 interfere with the mortar binding reaction. Sewage sludge can also be used for the production
117 of bricks, tiles and other ceramic materials (Amin et al., 2017; Hamood et al., 2017;
118 Rahman et al., 2017; Zhang et al., 2016).

119 Excess sewage sludge combustion is becoming a more and more frequent solution due
120 to the possibility of hygienisation of sludge and, at the same time, reduction of its volume. This
121 utilization technique generates a different type of waste, which can also be used in construction.
122 Ashes, in addition to the increased content of heavy metals, have a similar oxide composition
123 to cement clinker, they also show little pozzolanic activity, which suggests that they can be used
124 as an addition to mineral construction materials, cements or concretes (Tantawy et al., 2012).

125 Due to considerable and ever-growing amounts of the difficult to manage excess sludge,
126 strict regulations, and significant costs associated with utilization, modern methods of
127 development are sought (Hadi et al., 2015). The use of both unprocessed sludge and ashes in
128 the construction industry may prove to be a modern and environmentally beneficial way of
129 utilization. Due to increasingly stringent regulations related to the methods of sludge utilization,
130 more and more intensive research on the use of sludge is being carried out. There is no current
131 review in the literature showing the latest approaches to sludge management in the construction
132 industry. There is also no specific comparison showing which of the solutions is the most
133 optimal in terms of strength aspects, durability and metal leaching of the obtained materials and
134 their impact on the environment.

135 The main purpose of the article is to present the latest methods of using non-ash sewage
136 sludge in building and construction materials. The methods of using raw (unprocessed),
137 stabilized (e.g. with lime) or dried sludge as additives to concrete mortars, cement slurries,
138 construction products (e.g. blocks) and sintered/ceramic materials are presented. In addition,
139 several examples are described of the production of low strength materials intended mainly for
140 landfill applications and soil reinforcement. This publication does not contain information on
141 the use of ashes obtained after thermal utilization of sewage sludge, because the implementation
142 of such methods requires the construction of a thermal treatment plant, which inevitably

143 involves considerable financial outlays. In addition, thermal treatment of sludge seems
144 economically justifiable only for large wastewater treatment plants, e.g. those collecting sewage
145 sludge from agglomerations over 200.000 inhabitants. The production of building materials
146 from non-incinerated sludge may be an alternative for smaller sewage treatment plants, whose
147 operators are struggling with the problem of managing excess sewage sludge.

148 **2. Methods**

149 This study focuses on describing the methods of raw sewage sludge management in
150 construction industry. The ashes obtained after thermal utilization of sewage sludge, that could
151 be used as an additive to building materials, are not mentioned here since not all wastewater
152 treatment plants can afford to perform sewage sludge thermal utilization process. Advantages
153 and disadvantages of presented concepts are presented. The review is based on the scientific
154 literature but not exclusively. Studies published in technical journals and books chapters are
155 also mentioned.

156 **3. Physicochemical characteristics of excess sludge**

157 Sewage sludge is a liquid or semi-liquid waste resulting, inter alia, during the process of
158 biological and mechanical wastewater treatment, which consists of suspended and dissolved
159 organic and inorganic substances (Hamood et al., 2017).

160 In the literature one can find the term "biosolids", which defines the stabilized sludge.
161 Biosolids are usually sewage sludge originating from municipal wastewater treatment plants
162 processed in such a way (e.g. by aerobic stabilization or methane fermentation) that it can be
163 used, for example, to improve soil quality. Sewage sludge is the term referring to untreated
164 primary and secondary organic solids (Bondarczuk et al., 2016; Wang et al., 2008).

165 In North American legislatures, the semi-solid residue, which is an intermediate produced
166 in wastewater treatment plants, is also referred as biosolids (Oberg (Öberg) and Mason-Renton,
167 2018).

168 Sludge produced in wastewater treatment plants can come from various stages of
169 purification. Each of them generates sludge of slightly different properties. Basically, the
170 following can be distinguished:

- 171 • primary sludge – a result of mechanical pre-cleaning,
- 172 • secondary sludge – excess sludge created as a result of biological wastewater
173 treatment,
- 174 • sludge from chemical precipitation – formed, for example, during the removal of
175 phosphorus compounds, which are most often mixed with secondary sludge.

176 The composition and quality of produced sewage sludge is variable and depends on the
177 processing method and the share of industrial wastewater. In general, sewage sludge is
178 characterized by:

- 179 • high hydration, usually 99 % for unprocessed and 80-55 % for dehydrated sludge,
- 180 • high content of organic substances, 75 % dry matter (DM) for raw sludge, 45-55 %
181 DM for stabilized sludge,
- 182 • high content of Kjeldahl Nitrogen, 2-7 % DM, and phosphorus, 1-5 %, and in special
183 cases up to 15 % DM,
- 184 • various heavy metal contents (0.5-2 %, in some cases up to 4 % DM), depending on
185 the origin and processing technology,
- 186 • varied amount of pathogenic microorganisms; their type and amount depend on the
187 place of origin of sludge, the most is found in sludge from primary settling tanks
188 (Częstochowa University of Technology, 2004, Xu et al., 2013).

189 Sewage sludge is rich in organic substances easily absorbed by plants, such as nitrogen,
190 phosphorus, potassium, and, in smaller amounts, calcium, magnesium, and other
191 micronutrients. Thanks to the purification process, biogenic substances became more
192 concentrated in the sludge, which positively affects its quality. Sewage sludge also improves
193 the sorption capacity of the soil and contributes to the creation of a more optimal
194 environment for the development of microorganisms. On the other hand, this concentration
195 increases the content of heavy metals and toxic organic substances. It is mainly the content
196 of heavy metals in sludge that determines the possibility and way of using them for
197 agricultural purposes. The presence of heavy metals in trace amounts is advisable, as it is
198 necessary for the development of plants. However, in high concentrations the content of
199 these metals becomes a problem. Table 1 shows the average content of heavy metals in
200 selected types of sewage sludge. The most frequently occurring heavy metals are Cu, Cd,
201 Pb, Hg, Cr, which reach the sediments mainly as a result of industrial wastewater treatment
202 (Xu et al., 2013; Zhang et al., 2016).

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204
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208 Table 1. Average content of heavy metals in selected types of sewage sludge from
 209 wastewater treatment plants.

<i>Source</i>		<i>Element</i>	<i>Cu</i> mg/kg <i>DM</i>	<i>Zn</i> mg/kg <i>DM</i>	<i>Pb</i> mg/kg <i>DM</i>	<i>Cd</i> mg/kg <i>DM</i>	<i>Ni</i> mg/kg <i>DM</i>	<i>Cr</i> mg/kg <i>DM</i>	<i>Reference</i>
<i>Household wastewater</i>			213	750	52	2.0	30	117	(Cheng et al., 2014)
<i>Industrial wastewater</i>			2.5	1.3	59	2.8	106	111	
<i>Activated sludge</i>	France		149	548	18	0.6	26.4	27.6	(Tella et al., 2013)
	Senegal		200	930	62	2.0	44	120	
<i>Municipal sewage sludge</i>			433	2032	126	2.78	621	856	(Ščančar et al., 2000)
<i>Sewage sludge</i>			2.6-131.2	28-2436	0.4-194.0	0.08-16	0.4-25	2.8-2855	(Częstochowa University of Technology, 2004)
<i>Municipal sewage sludge</i>	Great Britain		562	778	221.5	3.5	58.5	159.5	(Cyprowski and Krajewski, 2003)
	Germany		275	834	67.7	1.5	23.3	50	
<i>Sewage sludge</i>			57	211	171	-	15	325	(Mulchanda ni and Westerhoff, 2016)
<i>Municipal sewage sludge</i>	Turkey		-	1684	60.7	4.4	78.9	263.4	(Kendir et al., 2009)
	USA		741	1202	134	7	43	-	(Lu et al., 2012)
	Australia (biosolids)		187.2	548	24.3	-	24.7	52.9	(Antunes et al., 2017)

210
 211 The occurrence of microorganisms in sludge depends on the standard of living in a given
 212 country, the health status of residents and the purification technique used. The sludge is
 213 dominated by pathogenic bacteria, viruses, fungi, protozoa and parasitic eggs (Częstochowa
 214 University of Technology, 2004).

215

216 **4. The main methods of excess sludge management**

217 The management of sewage sludge begins with its dewatering, stabilization and/or
218 hygienisation. The thus prepared sludge reaches the final stage ending with recovery or
219 disposal.

220 Thickening, as the basic unit process, consists in separating the solid phase from the liquid,
221 which allows to reduce the hydration of the sludge to about 90-95%. The sludge is then
222 subjected to conditioning in order to change its structure and properties, which is important in
223 the effectiveness of its further dewatering. The main purpose of conditioning is to accelerate
224 the sedimentation of the solid phase of sludge. Flocculation is used for this purpose, most often
225 by chemical means. Final dewatering, on the other hand, involves the further removal of water
226 to approx. 40 % DM, which brings the sludge to a more solid consistency. If the method of final
227 management so requires, the sludge is dried. Drying does not change the chemical composition
228 of the sludge, however it improves its calorific value in the case of thermal utilization methods
229 (Niesler and Nadziakiewicz, 2014).

231 4.1. Agricultural use and biological utilization

232 Sewage sludge in agriculture is most often used as a fertilizer improving soil quality and
233 revegetation of soilless soils. Drying the sludge or its partial dehydration facilitates its
234 application to the soil and reduces transport costs, whereas an omission of the process may lead
235 to adverse physical changes in the soil. The factors determining the possibility of direct use of
236 sewage sludge are: content of pathogenic organisms, consistency, concentration of heavy
237 metals and odour nuisance. If the sludge is applied as a fertilizer for arable crops, special
238 attention is paid to the above aspects, as their use must not worsen the quality of soil and the
239 obtained agricultural products (Cieřlik et al., 2015; Grobelak et al., 2016; řroda et al., 2013).

240 Composting is a beneficial method of recycling organic matter and nutrients. It consists in
241 an oxidative decomposition of organic substances with the participation of microorganisms at
242 elevated temperature, which can be carried out on the surface of the ground or in a bioreactor.
243 Composting can be divided into two stages: thermophilic phase and maturation phase. In the
244 former, mineral and humic substances are formed, while pathogens are eliminated.
245 Humification continues also in the maturation stage, thanks to which the total volume of waste
246 decreases. The finished product should not contain ammonia, its color should be dark brown
247 and the odour earthy (Y. Chen et al., 2014; Kosicka-Dziechciarek et al., 2016). In addition to
248 sanitary security, compost intended for use in agriculture should meet all ecological standards.

249 In the case of composts obtained from sewage sludge, the content of heavy metals is comparable
250 to their content in raw sludge, which can often disqualify the obtained compost as to its use for
251 agricultural purposes (Ignatowicz et al., 2011; Kulikowska and Gusiatin, 2015).

252 Methane fermentation is also a biological process, but it takes place under anaerobic
253 conditions. Anaerobic bacteria decompose biodegradable substances while producing biogas.
254 Biogas (a mixture of mainly CH₄ and CO₂) shows a high calorific value and can be used to
255 produce heat or electricity (Cao and Pawłowski, 2012).

256 Methane fermentation does not ensure complete decomposition of organic matter in the
257 added substrate. During this process, new microorganisms develop in the reaction liquid, which
258 results in a certain amount of new waste. Post-fermentation residue (the so-called digestate) is
259 not biodegradable. One of the methods of management is to pour it over the fields to improve
260 the quality of the soil. The presence of heavy metals, pathogens, as well as organic pollutants
261 (polychlorinated biphenyls, dioxans, furans, PAHs) may be a limitation here as well as in the
262 use of composts. In the case of this type of pollution, thermal methods of utilization,
263 i.e. pyrolysis, gasification, or incineration are used (Cao and Pawłowski, 2012; Wawrzyniak
264 and Zbytek, 2015).

265

266 4.1. Thermal utilisation methods

267 Before applying thermal utilization methods, sewage sludge must be appropriately pre-
268 treated. Most often it is a drying process, which is particularly justified when the sludge is
269 characterized by a high degree of hydration (Środa et al., 2013).

270 Combustion of excessive sewage sludge is becoming an increasingly used method of
271 utilization. Considering the restrictions related to landfilling and use in agriculture, it is
272 becoming more and more important mainly due to the disposal cost. The mechanism of sludge
273 combustion differs from the mechanism of coal combustion, mainly due to the significant
274 hydration of the substrate, mineral content and volatile fraction in the combustible substance
275 (Środa et al., 2015, 2012). Combustion is most commonly carried out in fluidized bed reactors
276 at a temperature of about 700 °C. The calorific value of dried sewage sludge is in the range of
277 12-20 MJ/kg, which is lower than the calorific value of coal but equivalent to the value for
278 brown coal. Due to combustion, the volume of the sludge decreases by approximately 95 % and
279 its mass is reduced to 1 % compared to the state before the process. Although ashes formed
280 after combustion are a sterile and inert product, the elevated amount of heavy metals is the



281 reason why they can be treated as hazardous waste (Środa et al., 2012; Tashima et al., 2017).
282 There are known cases when volume reduction reached only approx. 90 %.

283 High-temperature alternative processes can include, for example, pyrolysis and gasification.
284 Pyrolysis is the thermal decomposition of materials in an inert atmosphere resulting in three
285 fractions: gas – containing low molecular weight gases, liquid – containing volatile substances,
286 and a solid residue – char. Pyrolysis, unlike combustion, is an endothermic process (Samolada
287 and Zabaniotou, 2014).

288 Despite the advantage over conventional combustion in the context of fuel recycling and
289 energy recovery, pyrolysis of sewage sludge is problematic, as moist sludge requires more
290 energy to be heated. In addition, the condensing water vapour enters the liquid products, which
291 causes their quality to deteriorate, which translates into subsequent treatment costs. During the
292 process, the pressure in the reactor increases due to the large amount of steam generated, which
293 in turn causes a change in the composition of products (Gao et al., 2014).

294 In addition to energy-useful gases and the liquid fraction, char rich in carbon is also
295 obtained. The char from biomass (often called biochar) improves soil productivity and removes
296 impurities. As is the case with other methods of utilization, the use of biochar from sewage
297 sludge for agricultural purposes is conditioned by the content of heavy metals (Cao and
298 Pawłowski, 2012).

299 Gasification consists in converting a solid raw material into a gaseous product. Reactions
300 occurring in the gasification reactors are carried out with oxygen deficiency, which is why they
301 are endo- and exothermic transformations. Gasification takes place at temperatures between
302 700 and 900 °C. Then, cracking occurs and volatile compounds and carbon from biomass are
303 converted into a combustible gas mixture, which after removing ashes and tar can be used to
304 produce electricity and heat (Hernandez et al., 2011).

305 The problem with the management of solid residues after gasification is again related to the
306 heavy metal content. In the case of this technique, high temperature reduces the possibility of
307 these elements leaching from the residue, but it depends on the amount of oxygen introduced
308 during the process (Hernandez et al., 2011).

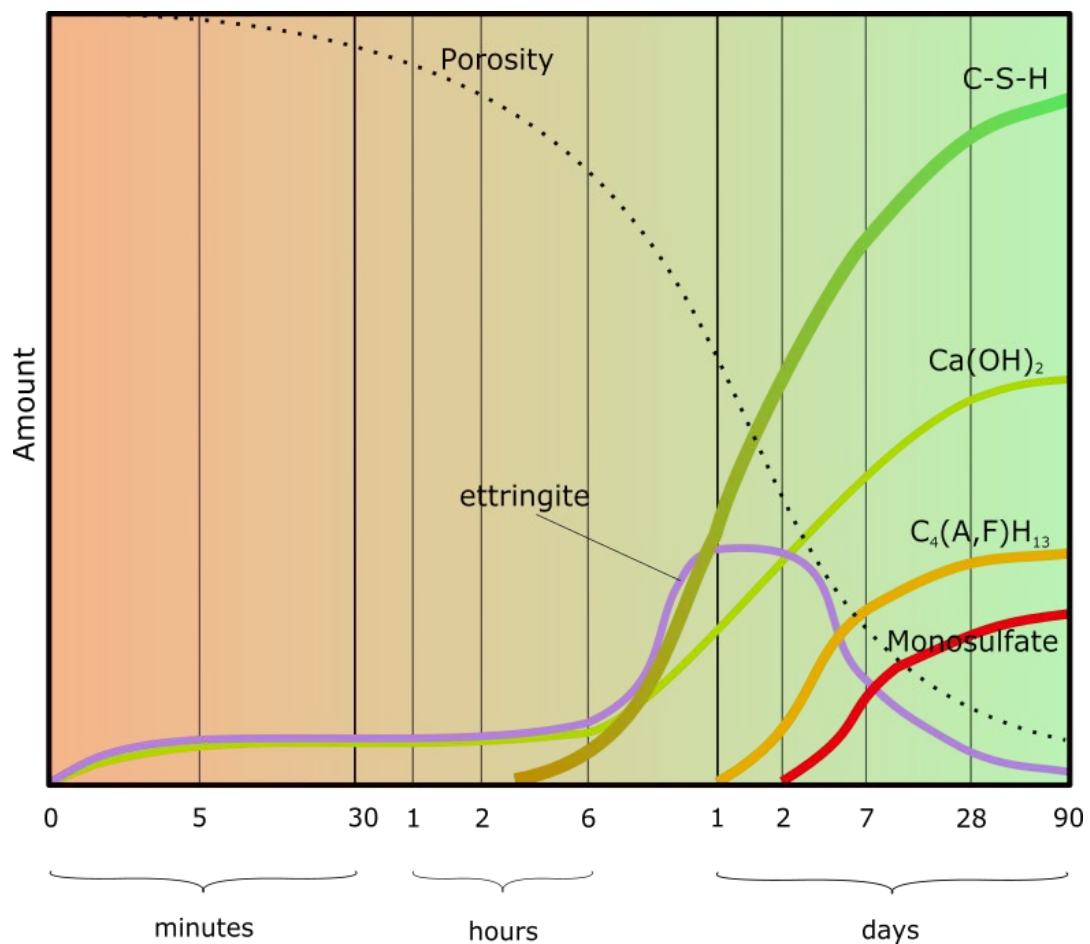
309

310 **5. Binding of cement mixtures and sintering of materials containing sewage sludge**

311 The main component of cements is clinker, a mixture of four main oxides: CaO, SiO₂, Al₂O₃
312 and Fe₂O₃, which comprises 95 % of its mass. As a result of thermochemical reactions between
313 components of cement-based materials, the basic phases are obtained: tricalcium silicate,



314 dicalcium silicate, aluminates and calcium aluminoferrites (Peukert, 2000). The development of
 315 structure in a cement slurry consists of three stages. In the first stage, the sodium hydroxide
 316 present in the slurry solution separates into a solid form. Calcium sulphate simultaneously
 317 passes into the solution, reacting with the present minerals, leading to the formation of
 318 sulphoaluminates and calcium sulphoferrates. The hydration process of aluminates is slowed
 319 down due to the formation of the two aforementioned minerals on their particles. In the second
 320 stage, the C-S-H phase (hydrated aluminosilicates) is created, which fills in the open spaces and
 321 together with ettringite (hydrated calcium sulphoaluminate) they form a compact structure. In
 322 the third stage, pores in the slurry are filled with short-fiber and lamellar C-S-H phases, which
 323 can take several months. The hardened slurry therefore includes: C-S-H gel phase, crystalline
 324 materials (portlandite and ettringite), unhydrated cement grains, capillary spaces and pores
 325 (filled with water or air), and thin films of water inside the slurry (Peukert, 2000). The schematic
 326 process of hardening the cement slurry is shown in Figure 2.



327
 328
 329
 330
 Figure. 2. Cement slurry binding scheme (Peukert, 2000)

331 The cements may also contain active additives affecting the strength of concrete or mortar,
332 i.e. natural or artificial pozzolanic additives. Natural pozzolans are mostly of volcanic origin.
333 The artificial ones include ashes from the combustion of bituminous coal, burnt clay and slate,
334 blast-furnace slag, silica fume or volcanic ash. Pozzolanic activity consists in binding lime in
335 the presence of water, which results in the formation of water-insoluble calcium silicates.
336 Thanks to the addition of ashes, from burning coal, to cement, its pozzolanic activity is
337 increased, which begins to manifest only after a few days from the beginning of the mortar
338 curing process (Peukert, 2000).

339 The use of cement additives is entirely justified both in environmental and in economic
340 terms. It gives the possibility of re-using waste material which improves the properties of the
341 final products. The presence of iron and unburned carbon is undesirable in the ash. Iron may
342 adversely affect the pozzolanic activity of ash, and carbon may increase the demand for water
343 during the production of, for example, concrete (Giergiczny et al., 2002).

344 Due to the large load of organic matter, the possible presence of pathogens or heavy metals,
345 and often the lack of the possibility of landfilling unprocessed sewage sludge, one of the most
346 commonly used methods of utilization is using sludge as alternative material to cover the slopes
347 of landfills or lining their bottom. It is the simplest and cheapest solution, allowing simultaneous
348 dehydration of the sludge, its hygienisation (the binding additives are usually highly alkaline)
349 and the creation of a low-strength, waterproof material.

350 During the production of cement mortars and concretes, it is necessary to use water, so using
351 raw sewage sludge as its partial or complete substitute is an interesting concept. This approach
352 also eliminates the need for prior dewatering. Hardened concrete or mortar immobilizes heavy
353 metals and organic substances contained in the sludge as a result of their encapsulation in a
354 cement matrix and the reaction between heavy metals and binder components.

355 Natural aggregates of various granulation are also used in structural concretes. To limit their
356 use in concrete mixtures, fine aggregate (sand) is replaced by partially dried sludge. The
357 presence of sludge in hardened mortars or concretes often leads to a deterioration of their
358 properties (Hamood et al., 2017; Mladenovič et al., 2017; Pavšič et al., 2014; Yang et al., 2017).

359 Production of bricks, roof tiles and ceramic materials from raw materials intended for
360 this purpose, as well as excess sewage sludge, is based on the sintering process, which is
361 possible due to the presence of similar elements, such as in clay. During sintering, complex
362 physical and chemical processes depend on the parameters of the process being carried out.
363 Sintering, in contrast to vitrification, consists in pre-compacting the fragmented material and



364 then heating the moulding at a temperature not exceeding the melting point of the ingredients.
365 The thus obtained sinter is cohesive and more durable than a moulding. If a mixture of materials
366 differing in the melting point is used, sintering is carried out at a temperature above the melting
367 point of at least one component. Heating the powdered or fine-grained components of the
368 mixture without bringing it to a liquid state causes the surface of the particles to begin to melt,
369 thanks to which the grains merge into a porous element (Pater, 2014; Wiśniewski et al., 2012).

370 Ceramic materials produced by mixing dried sewage sludge with other components are
371 characterized by porosity and uneven surface, which can affect both the strength and the water-
372 absorbency of such materials. On the other hand, the porosity may affect the frost resistance of
373 the materials produced in this way (Kadir et al., 2017; Zhang et al., 2016).

374 In order to improve the fire resisting and insulating properties, as well as reduce the mass
375 of concrete products, they are enriched with additives in the form of lightweight aggregates.
376 They are porous, hard and spherical ceramic aggregates characterized by different density and
377 water absorption capacity, depending on temperature. Sintering such materials at appropriately
378 high temperatures causes the aggregate surface to become glassy, and hence thicker and more
379 compact. The pores in the material are partially isolated and thus the lightweight aggregate
380 particles absorb less water (Lau et al., 2017; Tuan et al., 2013).

381

382 **6. The use of undewatered, stabilized and dried excess sewage sludge**

383 The storage of unprocessed sludge in EU landfills is prohibited (according to Landfill
384 Directive (99/31 / EC)). In some cases, it is possible to manage it, but it must be appropriately
385 processed. In Poland, it is possible to landfill sludge if it contains less than 5 % of organic matter
386 in DM, and the heat of combustion is less than 6 MJ/kg DM (Duda et al., 2014). In other
387 countries, legal restrictions may be less stringent, for example, the Chinese government,
388 according to CJ / T249-2007, allows the landfill use of sludge with moisture content less than
389 60 % (wet weight) and shear strength over 25 kPa (P. Chen et al., 2014). Many authors also
390 emphasize that due to good strength parameters, low water permeability and immobilization of
391 heavy metals, sewage sludge dewatered with new technologies or stabilized with binders has a
392 wider application than materials used as landfill lining or capping.

393

394 **6.1. Raw excess sludge constituting the material for covering landfill sites.**

395 The study by P. Chen et al. (P. Chen et al., 2014) presents a method of direct use of sewage
396 sludge to produce an alternative material for covering landfills. The material was made by

397 dewatering sewage sludge through a filter press. Using pressure up to 2 MPa during dewatering,
398 material characterized by a compact and durable structure was obtained from the sewage sludge
399 (pre-dehydrated to 60 % moisture). The initial de-watering process caused the introduction of
400 additional quantities of Fe, Al and Mg. Among other things, compressive strength of dehydrated
401 and dried sludge was determined. Due to the possibility of using sludge as a protective material
402 for the top layer of a landfill, water permeability was also determined. Some properties were
403 compared with clay loam, which is used as landfill capping material in China. The unconfined
404 compressive strength of the produced material ranged from 58 to 104 kPa and the undrained
405 shear strength from 29 to 52 kPa. Such diversified values of strength were obtained due to the
406 inhomogeneity of the material. It was also shown that water permeability of such material is
407 lower compared to clay. The permeability increased the longer the material was subjected to
408 water, but even after the 2-month test the permeability value still met the required standards.
409 The main metals found in the produced material were Zn and Ni, in smaller concentrations it
410 contained Hg, Cu, Cd, Cr and Pb, but their content did not exceed the values determined by
411 Chinese legal standards. The analysis of the results of the experiments carried out by the authors
412 indicates that sludge processed in that way can be used as an alternative material covering
413 landfills due to low water permeability and higher than required (25 kPa) undrained shear
414 strength (P. Chen et al., 2014).

415

416 6.2. Stabilization of sewage sludge with binders other than Portland cement

417 As mentioned earlier, additives such as ash from combustion of coal or biomass, blast
418 furnace slag or silica dust, are characterized by pozzolanic activity. This property was utilised
419 in a study by Mladenovič et al. (Mladenovič et al., 2017), where mixtures of two waste materials
420 were tested. Those materials were: municipal sewage sludge stabilized with lime, and ashes
421 after incineration of recycled paper wastes after decolourisation. The used sewage sludge could
422 not be managed in agriculture due to the excessive content of heavy metals.

423 On the basis of a mineralogical analysis of sewage sludge, a low content of mineral fraction
424 was indicated, while the ashes from recycled paper contained mainly calcite. The leachates from
425 the sample after 28 days of hardening were characterized by high pH, and heavy metal
426 concentrations were lower than in the case of leachates from raw sludge and did not exceed the
427 legal norms. The only exception was copper, the concentration of which in the leachates was
428 higher than that of the other metals, but it did not exceed the standards that building materials
429 applications must meet. Copper mobility is lowest in weakly alkaline solutions, while in

430 strongly alkaline solutions it can increase. The authors indicate that according to the Slovenian
431 law, the composite is suitable both for landfill capping and lining. Immobilization of heavy
432 metals in the material enables its use in building embankments or road foundations. In addition
433 to limiting leaching of heavy metals from sludge, an additional advantage of this solution is the
434 fact that sludge does not require dewatering, which is associated with energy saving
435 (Mladenovič et al., 2017).

436 The results of research on the use of excess sludge as landfill capping are described in the
437 work by Li et al. (Li et al., 2014). Innovation in the authors' approach was the addition of binders
438 as early as at the sludge dewatering stage. The sewage sludge used in the study was a mixture
439 of primary and secondary sludge of high hydration (97 %) from a municipal wastewater
440 treatment plant. The binder material used in the tests was fly ash from coal combustion.
441 The main ash constituents were SiO_2 (60 %) and Al_2O_3 (29.4 %), which were supposed to be
442 responsible for the pozzolanic reaction.

443 The dewatering procedure consisted in mixing raw sludge with ashes, lime and iron chloride
444 in several different proportions. The prepared mixture then went to a filter press where water
445 was removed from it at the pressure of 0.8 MPa. The use of lime and ashes not only improved
446 the sludge dewatering process, but also positively influenced the strength of the manufactured
447 products. Active SiO_2 , Al_2O_3 and CaO under the influence of moisture contributed to the
448 production of ettringite and the C-S-H phase. The number of hydration reaction products
449 increased with the time of binding of the presented material, which directly translated into its
450 strength. The values of unconfined compressive strength and shear strength, determined after
451 30 days of hardening, were in the following ranges: 600-800 kPa and 130-140 kPa respectively.
452 The material produced in this way was characterized by low water permeability
453 (values of $10^{-6} \text{ cm s}^{-1}$) and thus the risk of leaching of heavy metals and organic substances was
454 considered negligible. The material can be successfully used as landfill capping, but also as a
455 material for applications in the construction and building industries (Li et al., 2014).

456 In the work by Hwang et al. (Hwang et al., 2017), excess sewage sludge was used as a
457 component of controlled low-strength material (CLSM). It is a cement liquid material capable
458 of self-compacting, used to fill hard to reach places. In this case, the binders were fly ash from
459 one of the Taiwanese heat plants and granulated blast-furnace slag from a steel factory, which
460 were activated in the mixture with NaOH solution. The main components of the ashes were
461 SiO_2 – 64 % and Al_2O_3 – 20 %. The ones of the blast furnace slag were SiO_2 – 39 %
462 and CaO – 37.5 %. The tested mixtures were prepared by mixing fly ash with slag in a 7:3 ratio

463 together with dried sludge in amounts of 10 % and 20 % in relation to the mixture of binders.
464 The effect on the mixtures of different amounts of activator and water needed to make the
465 samples was also checked. The mixtures were analysed after 1, 3, 7 and 28 days in terms of
466 their compressive strength. The addition of sewage sludge negatively influenced the
467 workability of the mass and extended its setting time in comparison with mixtures of the same
468 composition, but without the participation of sludge. The influence of the addition of sewage
469 sludge to the samples increased their water absorption, which contributed to increasing their
470 compressive strength. The main microstructural phases in the obtained products were quartz
471 and a matrix of calcium silicate hydrates (C-S-H).

472 Samples more abundant in sewage sludge were characterized by a denser structure which
473 affected the compressive strength. The leachates from raw sediments and from the
474 manufactured products were both characterized by very low concentrations of heavy metals
475 (values of 0.01-0.05 mg/l) and, as a consequence, met the requirements of the Taiwanese
476 Environmental Protection Agency. The sample containing 10 % sewage sludge and 9 %
477 activator (presented as Na₂O) in relation to the binders was characterized by the best strength
478 parameters. In addition, its physicochemical properties met the standards of the Taiwanese
479 Department of Public Works. In the hardened materials only Cu and Zn (0.05 mg / L and
480 0.05 mg / L) were able to be determined, whereas concentrations of metals such as Pb, Cr, Ni
481 were below the limit of detection (0.005 mg / L). The values provided by the regulatory limits
482 for metals such as Pb, Cr or Cu must be below: 5.0, 5.0, 15.0 mg / L.

483 Although the addition of sewage sludge negatively influenced the fluidity of the mixture
484 and extended the setting time, it contributed to increasing its strength. Compressive strength of
485 the sample with the mentioned composition was 2.37 MPa after 1 day and 6.54 MPa after
486 28 days, indicating that the obtained material is suitable for use in public construction (Hwang
487 et al., 2017).

488 Similarly to the study by Hwang et al. (Hwang et al., 2017), the work by Pavšič et al.
489 (Pavšič et al., 2014) presents the possibility of utilization of unprocessed sewage sludge, by
490 using it, together with ash from biomass combustion, a material similar to CLSM. Additionally,
491 a possibility of incorporating waste aggregate into the mortar was investigated. Two mixtures
492 were tested: the first one was made of sludge and ash, while the second one was enriched with
493 recovered aggregate. The mortars were prepared by mixing sewage sludge (0.84 % DM) with
494 ash in a weight ratio of 1:1. The hardened samples were characterized by low compressive
495 strength values (about 1.6 MPa after 28 days).



496 Having compared the values presented in the study by Hwang et al. (Hwang et al., 2017),
497 the authors stated that the weakening of strength may be the result of the use of less active ash
498 and hydrated sludge, and the absence of an alkaline activator. Mixing unprocessed, hydrated
499 sewage sludge with ash causes its microbiological stabilization, which is the reason why a
500 neutral and low-strength material is obtained. It is also possible to use waste aggregate, however
501 in this case the compressive strength of the cured mixture is lowered. The obtained material can
502 be used as a foundation for road construction as well as to cover landfill sites. The content of
503 heavy metals in leachates from the samples turned out to be significantly lower than in the raw
504 materials. The high pH value and solidification processes in the hydrated matrix cause the
505 immobilization of heavy metals, which results in the obtained products being neutral in this
506 respect (Pavšič et al., 2014).

507 6.3. Stabilization of unprocessed sludge using Portland cement and additives

508 Unprocessed, raw sludge is highly hydrated. This property was used in the production of
509 concretes and mortars, by completely or partially replacing raw sewage sludge with water in
510 the mixtures (Hamood et al., 2017; Roccaro et al., 2015). The publication by Roccaro et al.
511 presents results of testing concrete mortar samples in which water was replaced with aerobically
512 and anaerobically stabilized sewage sludge in amounts ranging from 10 to 100 %. Compressive
513 strength of the control sample containing no sewage sludge was 44 MPa. Replacing water with
514 aerobically stabilized sludge in the amount of 10 %, caused the strength of the concrete sample
515 to decrease to 39 MPa. It was shown that the excess sludge can partially or completely replace
516 water in concrete mortar, however replacing the water with sludge even in the amount of 10 %
517 reduces the compressive strength of the obtained materials (Roccaro et al., 2015). In addition
518 to replacing water with sewage sludge, the mortar properties were additionally tested, where
519 the cement was replaced by ash from coal combustion (Hamood et al., 2017). The ash had a
520 high content of unburned carbon and large-sized particles, which is why it has not found its use
521 in conventional construction. The sewage sludge used in the research (with the hydration of
522 97.5 %) came from a municipal sewage treatment plant. In order to remove pathogens, it was
523 stabilized with lime (the pH of the sludge was lower than 12). Standard Portland cement CEM
524 I was used to make mortars. The ash consisted mainly of SiO₂ (45.1 %), Al₂O₃ (16.9 %), Fe₂O₃
525 (9.0 %), and CaO (2.0 %). The cement binder in mortar samples was replaced by ash in amounts
526 of 10 to 30 %. One group of samples was made using water (the reference samples), the other
527 group using undewatered sewage sludge. The fluidity of mortars produced on the basis of
528 sewage sludge was lower than those that were mixed with water. The most noticeable



deterioration of this quality was recorded for the mortar sample containing 30 % ash and prepared using sewage sludge. The analysis of the results indicates that the compressive strength of the samples increased with the duration of their curing time, regardless of the mixture composition. The control sample without the addition of ash was characterized by the highest value of compressive strength after 90 days of curing (about 25 MPa). Samples obtained from the undewatered sludge showed lower values of compressive strength regardless of time. After 90 days of curing, the strength values of the samples in which the ash constituted 10 and 20 % of the binder reached about 20 MPa. The strength of these samples did not deteriorate even after a year. The extended curing time and lack of strength deterioration after 90 days were caused by a pozzolanic reaction. The use of sewage sludge and 10 or 20 % of ashes instead of cement in the mortar can contribute to reducing the water demand during mortar production. Mixtures with this composition can be successfully used as mortars for internal applications, self-compacting mortars, and as cement materials for road construction (Hamood et al., 2017). The use of dried sludge for construction purposes was also dealt with in the work by Rahman et al. (Rahman et al., 2017), where the sludge originating from the textile industry was tested. The paper presents the possibility of replacing, with dried sludge, part of the cement in mortar samples and part of the sand in concrete samples. In the concrete samples, sand was the fine aggregate and stone chips were the coarse aggregate. Due to the fact that the size of the sludge particles ranged from 0.075 to 1.2 mm, it was used as a substitute for sand both in the mortars and the concretes. The mortar was prepared with cement to sand ratio of 1:3. The cement was replaced with sewage sludge in amounts up to 50 %. In a parallel test, the sand in the mortars was replaced with dried sludge in amounts of 20 to 80 wt %. The ratio of cement to fine aggregate and coarse aggregate in concrete samples was 1:2:4. The fine aggregate in the concrete was replaced by sludge in amounts of 20 to 100 %. After all samples had been prepared, their properties were tested after 28 days of curing. The analysis of the results of the conducted tests showed that the water absorption capacity increases in the samples of cement mortars together with the increase of the sludge content in the mixture, which is related to its high water binding capacity. Similarly, porosity increases with the amount of sludge in the mixture. Moreover, the addition of sludge causes the structure of mixtures to become more heterogeneous. Replacing 5 wt % of cement with sewage sludge reduced the compressive strength of the mortar sample by 15 % compared to the control sample (without sludge). Replacing 10 % of cement causes a rapid drop in the strength value from approx. 27 MPa to approx. 14 MPa, while 50 wt % of the sludge in the binder causes a drop in strength by 1/5



562 compared to the control sample. In the case of mortar samples, substitution of sand with sludge
563 decreases their strength. After replacing 25 wt % of sand with sludge, the compressive strength
564 decreases by 25 % (to 20 MPa), while the 50 % addition causes a 45 % strength reduction.
565 Replacing sand with sludge in concrete mixtures in the amount of 15 % causes a reduction of
566 their compressive strength from 24 MPa to 15 MPa. After 28 days of curing, samples of mortars
567 and concretes were kept in water for 60 days in order to test them for heavy metal leaching.
568 Because the sludge particles were enclosed in a cement matrix, the leaching of heavy metals
569 from the samples was minimal. The authors of the paper presented the results of research on Cr
570 and Cd leaching from finished products. The concentration of Cd found to be below the limit
571 of quantification and also lower than those required for inland surface water (0.01 mg/L). The
572 permissible concentration of Cr set by the Department of Environment in Bangladesh was
573 0.5 mg/L. Only in this case the determined concentration turned out to be slightly higher than
574 the normative value (0.73 mg/L) which was directly affected by the type of sewage sludge used,
575 because it came from the textile industry and had a high concentration of Cd. Due to the low
576 strength parameters, mixtures of mortars and concretes can be used in construction only where
577 low durability is allowed (Rahman et al., 2017).

578 The possibility of producing concrete bricks with the addition of sludge from a
579 pharmaceutical sewage treatment plant was also checked (Yamuna Rani et al., 2016). Dried
580 sludge from three different industrial pharmaceutical plants was used in the study. The samples
581 used were cement, lime, bentonite clay and reinforcing materials: ground fly ash, silica dust
582 and quarry dust in various proportions. The samples differed from each other in the content of
583 sewage sludge (from 10 to 35 %) and silica dust (from 15 to 30 %). The obtained samples were
584 left to cure for 28 days. The study also investigated the possibility of leaching metals from
585 samples. For this purpose, the samples were crushed to a particle size of less than 1 cm and
586 extracted, using a solution of acetic acid and sodium hydroxide, for 18 h at room temperature.
587 Analysis of the test results showed that the maximum compressive strength was achieved in
588 samples with the share of sludge of at least 10 %. Depending on the type of sludge used, the
589 strength values ranged from 17.2 to 18.6 MPa (for air-cured samples). A decrease in strength
590 was observed (irrespective of the type of sludge used) with the increase in the content of sludge
591 in the mixture, caused by the possible influence on the physical and chemical weakening of
592 bonds between the binders. Concentrations of heavy metals in the leachates were significantly
593 lower than in the case of unprocessed sludge, due to their binding in the silicate and aluminium
594 matrix. All the produced bricks met standards in terms of strength and heavy metal content in



595 the leachates. The production of bricks with the addition of sludge and other waste materials is
596 economically justified, because of the low cost of waste materials used for their production
597 (Yamuna Rani et al., 2016).

598 Another example is the work by Yang et al. (Yang et al., 2013) where an alternative
599 approach was demonstrated, namely using sewage sludge as an additive in a mixture of cement,
600 ashes and slag. An innovation in the authors' approach is the use of the autoclaving process that
601 improves the long-term strength of the obtained materials. Similarly to the aforementioned
602 work (Li et al., 2014), the binders were used as early as the sludge dewatering stage. Dewatering
603 consisted in the preliminary addition of ashes from the combustion of coal and lime to raw
604 sludge (a mixture of primary and secondary sludge) and its dewatering through a filter press.
605 The sludge was then air-dried until the water content was below 30 %. Fly ash was rich in SiO_2
606 and Al_2O_3 and because of that, together with lime and water in the mixture, it contributed to the
607 initiation of the pozzolanic reaction. The dewatered sludge was then used to produce
608 cementitious building materials. These materials contained furnace slag, as aggregate
609 ($d < 3$ mm), fly ash and Portland cement. The proportion of sewage sludge in the mixtures
610 ranged from 5 to 7.8 % DM of sludge. The process of autoclaving the materials was carried out
611 for 4 hours at 180 °C, under the pressure of 0.8 MPa. The samples were then tested for
612 compressive strength 24 hours after autoclaving. Long-term strength of the samples was tested
613 in frost resistance tests, accelerated carbonation, soaking and drying, and also heating and
614 cooling (wet-dry and heat-cool cycles). Autoclaved samples performed well in the long-term
615 strength tests, and elevated pressure and temperature ensured their full hygienisation. The
616 strength was affected by the amount of lime that was introduced into the mixture together with
617 the dehydrated sludge. As a result of curing of the binders, the sludge particles were retained in
618 the matrix of hydrated minerals, which translated into high strength of the tested samples and
619 prevented heavy metals from leaching. The leachates from the autoclaved samples contain
620 lower amounts of heavy metals and therefore comply with Chinese legal regulations. For the
621 mixture consisting of 50 % dehydrated sludge, 4.5 % ash, 39.5 % slag and 6 % cement, the
622 highest compressive strength values were obtained, ranging from 32.1 to 36.9 MPa. A parallel
623 increase in the share of sewage sludge (and, at the same time, lime), ashes and slag in the
624 mixture results in a deterioration of the strength of the samples. It was shown that the produced
625 materials can be used as construction building materials (e.g. building blocks) or landfill liners
626 (Yang et al., 2013).

627



628 6.4. Production of bricks and tiles with the addition of sewage sludge

629 An attempt was made to utilize municipal sewage sludge by including it in the mass destined
630 for the production of floor tiles (Amin et al., 2017). The sludge was dried, ground and added to
631 the basic mix. The blend was moistened with water (5 %) and compressed at 30 MPa to obtain
632 the desired shape of the product. After drying, the tiles were fired at temperatures from
633 1050 °C to 1150 °C. The share of sewage sludge in the total mass of the mixture ranged from
634 0 to 35 %. The main oxides included in the mixture used for the production of floor tiles were
635 SiO₂ (58.53 %), Al₂O₃ (22.97 %), Fe₂O₃ (3.68 %) and CaO (1.34 %). In the sewage sludge,
636 SiO₂ (9.46 %), Al₂O₃ (2.62 %) and P₂O₅ (3.81 %) predominated. The presence of sludge in the
637 mixture causes the formation of open pores as a result of the oxidation of organic matter, which,
638 along with the increasing content of sludge in the mixture, increases the water absorption
639 capability of finished products. In order to comply with the standards that must be met by floor
640 tiles, the content of sewage sludge in tile mixes should not exceed 15 %. Also, tiles should be
641 fired at 1150 °C, ensuring that the water absorption value reaches 10 %. The addition of 5 % of
642 sewage sludge lowered the flexural strength (modulus of rupture) of tiles fired at 1150 °C from
643 approx. 29 MPa to 23 MPa. At the same time, a 10 % addition caused a drop to a value of
644 around 18 MPa. According to ISO 13006/2012, which the authors refer to, tiles containing
645 5 %, 7 %, and 10 % of sludge, fired at 1100 °C, 1150 °C, 1150 °C respectively, can be used.

646 The production of bricks with the addition of sewage sludge is becoming a topic of interest
647 for scientists. In the work by Zhang et al. (Zhang et al., 2016), the object of study were bricks
648 made with lake sediments, slag and sewage sludge. All of the components were dried and
649 ground to a particle size of < 2 mm. After adding an appropriate amount of water, bricks were
650 formed and fired at 950 °C. In each of the used materials, there were oxides such as: SiO₂,
651 Al₂O₃, Fe₂O₃ and CaO, the last two having the highest concentration in sediments. During the
652 firing of bricks containing sludge, the additional heat resulting from the oxidation of organic
653 matter melted the components of the mixture together. This influenced the number of open
654 pores in the final product, and thus, the ability to absorb water was lower than in the case of the
655 mixture of lake sediments with slag. The presence of closed pores also reduced the thermal
656 conductivity of bricks (0.533 W/m·K) compared to samples without sludge. Compressive
657 strength of a brick containing 5 % sewage sludge, 85 % of lake sediments and 10 % slag was
658 lower by 38 % compared to a mixture without sludge (only lake sediment and slag). The
659 compressive strength of this sample, 20.5 MPa, was in line with Chinese strength standards.
660 Sewage sludge can be used in mixtures for the production of bricks, which is a modern form of



661 utilization. Their presence in the mixture ensures that the bricks shrink less during the process
662 of drying before firing and the finished products better insulate heat. On the other hand, the
663 compressive strength and frost resistance of the obtained products is lowered (Zhang et al.,
664 2016).

665 In the study by Kadir et al. (Kadir et al., 2017) clay was used as the main component of the
666 mixture instead of lake sediments. Both raw materials – clay and sewage sludge – were dried.
667 The proportion of sludge in bricks ranged from 0 to 20 %. The bricks were fired at 1050 °C.
668 The composition of oxides contained in both clay and sludge was similar. Mainly SiO₂, Al₂O₃
669 and Fe₂O₃ were determined. In contrast to clay, sewage sludge was characterized by a high
670 P₂O₅ content (approx. 7 %). It was noted that the higher the content of sewage sludge in the
671 mixture, the more the samples shrink during firing. The authors add that bricks of good quality
672 should have a maximum shrinkage value of 8 %. For the tested bricks, the shrinkage value was
673 lower than the mentioned 8 %. Increasing the share of sewage sludge in the mixture also affects
674 the density of bricks, which decreases with the increasing content of sediments due to the high
675 content of organic matter. Water absorption, similarly as in the aforementioned research,
676 increases together with the content of sediments. Bricks without the addition of sewage sludge
677 reached a compressive strength of approx. 27 MPa. The addition of only 5 % of sludge caused
678 a drop in strength to 12.6 MPa. This decrease is related to the formation of pores in finished
679 products as well as lower sintering temperature compared to the previous tests (Zhang et al.,
680 2016). The authors indicate that the use of sewage sludge for the production of bricks may be
681 an alternative method of its utilization, however its excessive addition (20 %) causes a
682 significant weakening of the manufactured products. The share of 5 % sewage sludge in the
683 mixture qualifies the obtained bricks as high-strength materials (Kadir et al., 2017).

684 Soil, sand, and fly ash can also be used as substrates for the production of bricks
685 (Tanpure et al., 2017). The proportion of sludge ranged from 10 % to 50 %, while the fly ash
686 content was constant in each of the samples (12 %). Similarly to the previously presented test
687 results, it was shown that as the percentage of sewage sludge in the mixture increases, so does
688 water absorption. A brick containing 10 % of sludge was characterized by a compressive
689 strength value of 3.5 MPa. This value decreased along with the increasing content of sludge.
690 For a 50 % share, a value of only 2.5 MPa was obtained. Such a low strength compared to the
691 results of the tests presented by Kadir et al. (Kadir et al., 2017), probably indicates the use of
692 improper substrates for the production of bricks (Tanpure et al., 2017).

693 The work by Ukwatta et al. (Ukwatta et al., 2015b) presents the use of biosolid in fired
694 bricks. In the studies, the authors used standard brick soil and biosolids, which came from
695 12-year-old stockpiles. Prior to testing, all samples were dried before adding them to the brick
696 mass. The proportion of biosolids in bricks was 25 % of the mixture before firing. In parallel,
697 a series samples were prepared without the participation of biosolids. The process of making
698 bricks consisted in wetting the mass to approx. 20 %, pressing it to the appropriate size and
699 drying it in the air for 24 hours. Then the prepared bricks were fired in a temperature of
700 1100 °C for 3 hours. The elemental composition of the bricks obtained was similar. The main
701 oxides found in the bricks were SiO₂, Al₂O₃ and Fe₂O₃. The content of most oxides in bricks
702 with the addition of biosolids was comparable to the control sample. Differences were observed
703 only in the case of P₂O₅, which was nearly 4 times more than in the control sample. The
704 compressive strength value of bricks with the addition of biosolids ranged from 25.9 to
705 16.2 MPa. In the case of a control sample, this value was 36.1 MPa. The reduction in strength
706 is related to the higher porosity of the bricks obtained in relation to the control sample. Bricks
707 with a 25 % share of biosolids were characterized by lower density, lower thermal conductivity
708 and higher porosity, which was caused by the burning out of organic matter. The obtained
709 bricks, despite the reduced compressive strength in relation to the control sample, were more
710 durable than the required strength value in the Australian Standards (3 MPa) (Ukwatta et al.,
711 2015b).

712 The same authors in another paper (Ukwatta et al., 2015a) also presented the influence of
713 the percentage of biosolids on the properties of bricks produced. The materials used in the
714 research were the same substrates as in the work (Ukwatta et al., 2015b). Samples contained
715 from 5 % to 50 % biosolids, while the control sample was made of bricks without biosolids. In
716 the case of this work, the authors fired samples at a lower temperature, which was 1020 °C.
717 Finished products have absorbed less water than expected by Australian standards.
718 The dependence was found that along with the increase in the proportion of biosolids in bricks,
719 the water absorption increases. The addition of up to 50 % biosolids caused a drop in the
720 compressive strength value of fired bricks by 40 %. Nevertheless the value was higher than
721 predicted by the Australian Standards. Therefore, the concentration of Cu in bricks containing
722 biosolids ranged from 0,025 to 0,030 mg/L, while Australian Standards required 200 mg/L.
723 In addition, the presence of significant amounts of organic matter in bricks allows to reduce the
724 energy demand during firing bricks. The results of studies on the possibility of leaching heavy
725 metals from bricks containing biosolids proved to be much lower than acceptable regulatory



726 limits. According to the authors, you can successfully use bricks, in which the content of
727 biosolids is not more than 50 %, because such bricks are characterized by high quality and good
728 mechanical and physical properties (Ukwatta et al., 2015a).

729 Wang et al. (Wang et al., 2011) presented the results of research on bricks made from
730 sewage sludge from the industrial sewage treatment plant and shale. The sludge and shale
731 samples were dried and screened through a 2 mm sieve before brick preparation. The weight
732 fraction of dry sludge in the samples ranged from 0 % to 15 %. Samples, after forming and
733 drying, were burnt at 960 °C for 2 hours. The strength of the prepared samples depended mainly
734 on the share of sludge in the total mass. The highest strength was demonstrated by samples of
735 bricks with 5 % addition of sewage sludge (about 15 MPa), where the compressive strength of
736 the control sample without sludge was 25 MPa. The authors indicate that the share of sludge in
737 bricks should not be higher than 9 % because higher contents do not meet the requirements for
738 bricks strength by Chinese National Standard for Fired Bricks. As in the other works mentioned
739 above, the porosity with the share of sludge in bricks increases and heat conductivity decreases.
740 As a result, the insulation properties of bricks are better than controls. Samples of bricks
741 produced were also tested for leaching of heavy metals. Concentrations of heavy metals
742 (Cr, Cd, Pb, Zn, As, Hg, Cu) did not exceed the acceptable limits (according to
743 GB5085.3-1996), what is more the marked concentrations were a few orders of magnitude from
744 those presented in the standard (Wang et al., 2011).

745 The work by Mozo and Gómez (Mozo and Gómez, 2016) presents the results of research
746 on the properties of bricks containing standard clay for making bricks and biosolids in an
747 amount of 5 to 15 % of biosolids. The control sample consisted of bricks without their addition.
748 Due to the fact that the properties of the final products are influenced by the particle size of the
749 used substrates, all raw materials have been ground to a particle size from 70 µm to 1 mm. The
750 formed bricks were fired at different temperatures: 950 °C, 1000 °C and 1050 °C. Both raw
751 materials were characterized by a high content of quartz. The presence of gibbsite and calcite
752 in biosolids makes using them in brick mass a good solution. According to Colombian
753 requirements for compressive strength of bricks (NTC 4205), this value for nonstructural
754 masonry units is 14 MPa, while for structural masonry units it is 20 MPa. As in other works,
755 the compressive strength of bricks decreases with the participation of biosolids and lowering
756 the sintering temperature. The control sample had a compressive strength of 34.05 MPa
757 at 1050 °C and a 5 % share of biosolids in bricks resulted in a drop in strength to 23.8 MPa.
758 According to the authors of the work, the presence of biosolids minimizes the risk of occurrence



759 of deformations and cracks during the drying process. Bricks with only 5 % content of biosolids
760 fired in 1050 degrees meet the mentioned standards. The authors did not present information
761 on the leaching of heavy metals from bricks in their work (Mozo and Gómez, 2016).

762 6.5. Production of concretes with lightweight aggregate from sewage sludge

763 Sewage sludge does not have to be included directly in mortars. As mentioned earlier, this
764 causes a reduction in the strength of the obtained concrete. In the construction industry,
765 lightweight concrete mixes are used, which include lightweight aggregate. This aggregate can
766 be modified with municipal sewage sludge, although it may cause the obtained concrete to have
767 a higher water absorption capacity.

768 The research by Suchorab et al. (Suchorab et al., 2016) presents the possibility of using
769 sewage sludge as an additive for the production of lightweight aggregate and concrete.
770 Lightweight aggregate was made of clay with the addition of 10 % sewage sludge from the
771 municipal wastewater treatment plant. The precipitate was dried to a solid mass, ground and
772 mixed with clay. To obtain the right consistency of the mass, an appropriate amount of water
773 was added and balls were formed. Dried balls were sintered at 1150 °C for 30 min. The obtained
774 concrete with lightweight aggregate had higher porosity, and hence lower density, compared to
775 a concrete with commercial lightweight aggregate. Due to the possible high water absorption
776 capacity of the aggregate, an impregnating agent was used in the mortar. Mortar with
777 lightweight aggregate containing sewage sludge absorbed much more of the impregnating
778 agent, which translated into much lower water absorption of the hardened concrete compared
779 to the concrete with commercial aggregate. It also shows that the aggregate is more porous and
780 has a well-developed surface. The addition of sewage sludge to aggregates also reduces thermal
781 conductivity of concretes with its addition by approx. 7-10 % compared to concrete with the
782 addition of a commercial aggregate. The compressive strength of concretes with an aggregate
783 containing 10 % of sludge reached the value of 11.1 MPa. The use of such an aggregate resulted
784 in a 29.5 % decrease in strength compared to the control sample. The article presents the results
785 of tests on leaching of heavy metals from obtained aggregates. The concentrations of Cr, Cd,
786 Cu, Ni, Pb and Zn in the leachate was much lower than the tolerable values (Suchorab et al.,
787 2016).

788 The materials used for the production of lightweight aggregate in the work presented by
789 Franus et al. (Franus et al., 2016) were mechanically dewatered sludge (part of the wastewater
790 came from industry) and clay. Both substrates were dried and ground to a particle diameter of
791 less than 0.5 mm. As in the case of the research results presented in the article by Suchorab et



792 al. (Suchorab et al., 2016), the amount of dried sludge in the clay mixture was 10 % (by weight).
793 The balls formed from the mixture were dried and fired for 30 min at 1100 and 1150 °C. The
794 physical properties of the obtained aggregates did not differ significantly from similar
795 aggregates of commercial origin. Aggregates produced at higher temperatures showed higher
796 porosity due to the production of gases as a result of the decomposition of organic matter, but
797 nevertheless met the requirements for water absorption. Compressive strength of the aggregate
798 fired at 1100 °C degrees was nearly six times higher (4.64 MPa) than the aggregate fired at
799 1150 °C. This is due to the presence of a glassy film and a higher number of pores in the
800 aggregate fired at higher temperatures. An analysis of leachates showed that sintering of sludge
801 into lightweight aggregates prevents the heavy metals contained in them from leaching. This is
802 caused by the presence of calcium, sodium and magnesium aluminosilicates in the clay, which
803 have the capacity for heavy metal sorption. Both of the obtained aggregates can be used as
804 additives to concretes used in the insulation of floors or ceilings, or for the construction of
805 curtain walls (Franus et al., 2016).

806 For the production of lightweight aggregate, two waste materials can be used
807 simultaneously – glass and sludge from sewage treatment plants (Tuan et al., 2013). The study
808 used wet sludge containing 70-80 % moisture. The waste glass was pre-dried and ground in a
809 ball mill to particles smaller than 150 µm. The proportion of sewage sludge in the mixtures
810 ranged from 50 to 90 %. Depending on the composition, the aggregates were fired at
811 temperatures of 830 to 1100 °C. Due to its best properties, an aggregate made of 70 % sludge
812 and 30 % glass (fired at 970 °C) was used in the concrete. The control sample was a concrete
813 with a natural coarse aggregate. Apart from the mentioned aggregates, the concrete also
814 consisted of: sand, ash and a plasticizer. The main oxides occurring in sludge included: SiO₂,
815 Al₂O₃, Fe₂O₃, CaO as well as P₂O₅, which constituted as much as 15 %. In the case of glass
816 waste, the main oxides were SiO₂, Al₂O₃ and CaO. The addition of waste glass can reduce the
817 sintering temperature due to the presence of Na₂O in it, which translates into energy savings.
818 Water absorption decreases when the sintering temperature rises, similarly to when there is
819 more waste glass in the sample. The sintering temperature is also important, because, for
820 example, a blend with 30 % glass content becomes more porous when the sintering temperature
821 increases. When sintering the mixture at a temperature of 900-970 °C, it swells and the coating
822 melts, thanks to which the pores are closed. Increasing the temperature further causes the pores
823 to start to collapse. The strength of aggregates depends mainly on their composition, in general
824 the more waste glass in the mixture, the higher the compressive strength of aggregates. Concrete



825 with the addition of aggregates with a content of 70 % of sludge and 30 % waste glass, sintered
826 at 970 °C, can be considered a good quality building material. After 28 days it had a
827 compressive strength of 49.46 MPa, which meets the strength requirements in accordance with
828 ASTM C330 and ACI 318 for structural concretes (the standard is 17.2 MPa)
829 (Tuan et al., 2013).

830 The work by Lau et al. (Lau et al., 2017) presents the method of producing lightweight
831 aggregates from lime-stabilized sewage sludge and ash after palm oil combustion.
832 As mentioned in the paper by Tuan et al. (Tuan et al., 2013), glass waste has a high content of
833 Na₂O, which reduces the sintering temperature. The use of sodium silicate in the mixture yields
834 a similar effect. Mixtures of sewage sludge, ash after palm oil combustion and sodium silicate
835 were sintered at three different temperatures: 1160, 1180 and 1200 °C. The main oxide present
836 in the sewage sludge (probably due to its stabilization) was calcium oxide (41.53 %), while in
837 the ash it was SiO₂ (59.13 %). The sewage sludge and ashes were dried and ground to a fine
838 powder. Both substrates were sieved to obtain particles smaller than 150 µm. The percentage
839 of sludge used ranged from 40 % to 60 %. Three series of tests were carried out. In the first
840 two, 10 and 15 % of sodium silicate was added to the ash and sludge mixtures, respectively.
841 The last series did not contain sodium silicate. It was shown that the higher the ash content in
842 the mixture, the higher the density of the fired aggregates. Due to the fact that the ash after palm
843 oil combustion had a lower melting point, it filled the spaces between the remaining particles
844 when melting. In the samples without the addition of sodium silicate, the aggregates had high
845 porosity and low bulk density, which resulted in an increase in the water absorption capability
846 and reduced the compressive strength. The addition of a silicate affected the strength of the
847 aggregate, which increased together with its content. Aggregates with a content of 40 and 50 %
848 of sludge with a 15 % addition of silicate, fired at 1160 °C, had a compressive strength of 8.1
849 and 7.4 MPa, respectively. Such values of compressive strength and density of aggregates
850 qualify them as lightweight aggregates (bulk density below 1200 kg/m³ – in accordance with
851 BS EN 13055) (Lau et al., 2017). For the purpose of summarizing, all materials containing
852 sewage sludge which can be used in the construction industry are listed in Table 2. For a better
853 comparison of material properties, the table also includes compressive strength values for
854 samples with the most optimal composition (in terms of properties and strength).

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Table 2. Comparison of the properties of building materials containing sewage sludge

Type of building material (main use)	Share of binder in product weight [%]	Share of sewage sludge in product mass [% DM]	Type of sewage sludge used	Binders and additives	Compressive strength after 28 days of curing [MPa]	Other possible applications	Comments	Reference
<i>Material for covering landfill sites</i>	-	100	Sludge stabilized with lime	-	0.058-0.104	-	-	(P. Chen et al., 2014)
	50 57 62.5	50 43 37.5	Sludge stabilized with lime (hydration approx. 84%)	Ash after waste paper combustion	NDA	Construction of road base and embankments	-	(Mladenovič et al., 2017)
	66.6	33.4	Mixture of primary and secondary sludge (hydration approx. 97%)	Ash after coal combustion, lime and iron chloride in a ratio of 1: 1: 0.3	0.7-0.8	The construction and building industry	The mixture of ash, lime and iron chloride was treated as a binder in the calculations.	(Li et al., 2014)
<i>Controlled low-strength material (CLSM)</i>	59	4.8	Dried sewage sludge from a municipal sewage treatment plant	Ashes after coal combustion, granulated blast-furnace slag, NaOH	6.5	Material for use in public construction	The ratio of blast furnace slag to ash was 7: 3	(Hwang et al., 2017)
	50	0.42	Sewage sludge with 99.2% hydration	Ash from biomass combustion	1.6	Material for coverage of landfill sites or base for road construction	-	(Pavšič et al., 2014)
	40.4	0.41		Ash from biomass combustion, waste aggregate 0/2 mm	1.4			

<i>Concrete</i>	63.5	4.1*	Aerobically stabilized sludge	Cement, no information on the aggregate	39	-	*-The share of sewage sludge (wet weight)	(Roccaro et al., 2015)
	14.3	4.3	Dried sewage sludge from the textile industry	Cement, sand, crushed stone	15	Low-strength construction materials	The calculations did not take into account the weight of water needed for mortar preparation. Sand to stone ratio was 1:2,4	(Rahman et al., 2017)
<i>Mortar</i>	16	0.32	Sludge from a municipal sewage treatment plant (97.5% hydration)	Cement, ash from coal combustion, sand	12-14	Mortar for internal use, materials for road construction	Ash content in the binder mass: 10%	(Hamood et al., 2017)
	23.75	1.25	Dried sewage sludge from the textile industry	Sand	Approx. 23	Low-strength construction materials	Substituting cement with sludge	(Rahman et al., 2017)
	22.5	2.5			Approx. 14			
	25	7.5			Approx. 25			
25	18.75	Approx. 20						

<i>Bricks/concrete blocks</i>	25	10	Sludge from the pharmaceutical industry	Cement, fly ash, silica dust, lime, bentonite, mine dust	17.2-18.6	-	Cement, lime and bentonite in a ratio of 1: 1: 0.5 were treated as a binder.	(Yamuna Rani et al., 2016)
	32.4	6.5	Mixture of primary and secondary sludge from municipal sewage treatment plants	Cement, fly ash, lime, slag	32.1 – 36.9	Material for covering landfill sites	Cement and lime in a ratio of 1:3.6	(Yang et al., 2013)
<i>Sintered products</i>	95	5	Dried sewage sludge from a municipal sewage treatment plant	A standard mixture for the production of tiles	23*	Floor tiles in accordance with ISO 13006/2012	Firing temperature: 1150°C 1150°C 1100°C * - Flexural strength	(Amin et al., 2017)
	90	10			18*			
	95	5			17*			
	95	5	Dried sewage sludge	85% lake sediments, 10% slag	20.5	Bricks	Firing temperature 950°C	(Zhang et al., 2016)
	99	1	Dried sewage sludge	Clay	22.3	Bricks	Firing temperature 1050°C	(Kadir et al., 2017)
	95	5	Dried sewage sludge	Clay	11.3	Bricks	Firing temperature 1050°C	(Kadir et al., 2017)
90	10	Dried sewage sludge	Soil, sand, fly ash	3.5	Bricks	NDA	(Tanpure et al., 2017)	
75	25	Dried biosolids	Standard brick soil	16.2 – 25.9	Bricks	Firing temperature 1100°C	(Ukwatta et al., 2015b)	

	95	5	Dried biosolids	Standard brick soil	37	Bricks	Firing temperature 1020°C	(Ukwatta et al., 2015a)
	95	5	Industrial sewage sludge	Shale	14.7	Bricks	Firing temperature 960°C	(Wang et al., 2011)
<i>Lightweight aggregate</i>	90	10	Dried sewage sludge from the municipal sewage treatment plant	Clay	NDA	Aggregate for the production of light concrete	Firing temperature: 1150°C. Concrete with the addition of 35% aggregate had a compressive strength of 11.1 MPa	(Suchorab et al., 2016)
	90	10	Dried sewage sludge from the municipal sewage treatment plant	Clay	4.64 0.79	Aggregate for the production of light concrete	Firing temperature: 1100°C 1150°C	(Franus et al., 2016)
	30	70*	Wet sewage sludge (hydration 70-80%)	Glass powder	NDA	Aggregate for the production of light concrete	*- The share of sewage sludge (wet weight) Firing temperature: 970 ° C Concrete with the addition of approx. 20% had a compressive strength of 49.46 MPa	(Tuan et al., 2013)

	60 50	40 50	Dried sewage sludge stabilized with lime	Ash after palm oil combustion, sodium silicate	8.1 7.4	Aggregate for the production of light concrete	Firing temperature: 1160°C In both mixtures, sodium silicate accounted for an additional 15% of mass	(Lau et al., 2017)
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7. Conclusions

Sewage sludge can be considered as a potentially attractive addition to building materials due to, among other things, their physicochemical properties. The main mineral components of sewage sludge include calcium, iron and aluminium compounds, which, in the form of oxides, are included in cement mortars and other commercially used building materials. The paper presents only the methods for the production of alternative building materials based on the use of non-incinerated sewage sludge, as an additive or base material. The presented possibilities of sewage sludge management can be particularly attractive for owners and operators of small sewage treatment plants, where the implementation of methods based on thermal utilization of sewage sludge is considered economically unjustified.

The durability of materials obtained by stabilizing sewage sludge with binding additives depends mainly on the type and amount of these additives. The use of fly ash is a beneficial solution because the stabilized sludge is characterized by higher strength than the sludge only dewatered through a press. The inclusion of sewage sludge in mixtures for the production of low-strength materials (CLSM) is usually associated with a decrease in their strength. The contribution and quality of the binder has the greatest impact on the strength of such materials. The binders used may be characterized by low pozzolanic activity, therefore a good solution is the use of an alkaline activator, which increases the strength of the hardened materials. The use of dried or undewatered sludge in concrete mixes is usually associated with a decrease in strength after curing, compared to the control mixtures. It is worth noting that the higher the cement content in the mixture, the greater the strength of concrete samples, even if there is a significant amount of sewage sludge in the mixture. Just like in concrete, the amount of cement in the mortar is the main factor affecting its strength. Replacing cement with sewage sludge is not a good solution, because its share in the mixture decreases, which directly translates into a lower strength of the hardened materials. A more advantageous solution is the use of sewage sludge as a partial substitute for fine aggregates (e.g. sand).

The deterioration of strength of cementitious materials containing sewage sludge compared to materials without it does not mean that it will not be possible to use the produced materials in construction. With competitive prices and a precise characterization of products, it is possible to determine the applications of such materials, even if their strength is reduced. It is essential that the manufactured building materials do not pose a threat to the environment, which has been proven in many presented cases.



Sintering of sewage sludge into lightweight aggregates and ceramic materials is also a rational approach, however it requires a significant amount of energy to achieve the appropriate sintering temperature. The production of lightweight aggregates with the addition of sewage sludge is a very promising method of its utilization, because the obtained material is inert and depending on the components used may even be more durable than commercial aggregates. Concretes with a lightweight aggregate have similar strength to concretes with commercial additives. In their production, the sintering temperature and the type of materials used are very important. Probably the best solution is to use waste glass for production. It allows to incorporate a significant amount of sewage sludge into the mixture, the sintering temperature is relatively low, and the produced material is durable, inert and very strong. However, the gases that are produced during firing may be a problem, as sludge may contain dangerous volatile organic substances.

The sewage sludge is also responsible for the different properties of building materials of the same group, as it may have different physicochemical properties. Therefore, for each case the method of managing excess sludge should be designed separately. For this reason, it is not possible to select one, most optimal method of producing building materials with the use of sewage sludge.

In vast majority of studied cases heavy metals are not leached from produced construction materials while they are embedded in the matrix. Even if heavy metals are leached from obtained products, the concentrations in leachates are negligible, often below the limits of detection and below the highest acceptable regulatory values. However, such test should always be performed since if higher amount of raw sewage sludge is used for construction material production, the possibility of heavy metals leaching is rising.

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