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

Lesław Świerczek[1], Bartłomiej Michał Cieślik[2], Piotr Konieczka[3]

[1,2,3] Gdańsk University of technology, Faculty of chemistry, Department of Analytical Chemistry
Phone: +48 58 347 16 01 [1,2], +48 58 347 21 10 [3]
e-mail: lesswier@student.pg.edu.pl [1], cieslik1988@wp.pl [2], piotr.konieczka@pg.edu.pl [3]

1. Abstract

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

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

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

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

1. Introduction

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

Sewage sludge management is a problem not only in European countries. It also applies to Asian countries. In Japan, from 1990 to 2004, an increase in the production of sewage sludge was observed by as much as 170 %. Currently, more than 2.2 million tonnes of dry matter of sediments is produced in Japan (Hong et al., 2009). This country, considered as one of the most developed, uses a number of methods for the management of sewage sludge or biosolids based on the recovery of energy from them (Christodoulou and Stamatelatou, 2016). Also in China, since 2007 to 2013 a rapid increase in the production of sewage sludge has been recorded, which was associated with the sudden development of sewage sludge treatment plants. In 2013, 6.25 million tonnes of DM of sewage sludge was produced in China. The amount of sludge per capita is much lower than in developed countries, but it is probably related to the differ, sometimes outdated, sewage sludge management methods and the size of the population (Yang et al., 2015). In the case of Australia, low population density and relatively small production of sewage sludge (about 303000 tons of DM biosolids per year) means that their management is subject to much public scrutiny (Pritchard et al., 2010). In less developed countries, for e.g. countries of Africa, Asia or Latin America, the number of wastewater treatment plants is considered small (per capita). As a result, the utilization of sewage sludge or biosolids is minimal or not carried out at all. In addition, in many countries, there are no regulations regarding sewage sludge management, which is why sewage from septic tanks goes to water bodies or direct into soil, which has a negative impact on the environment and public health. (Drechsel et al., 2015)

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

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

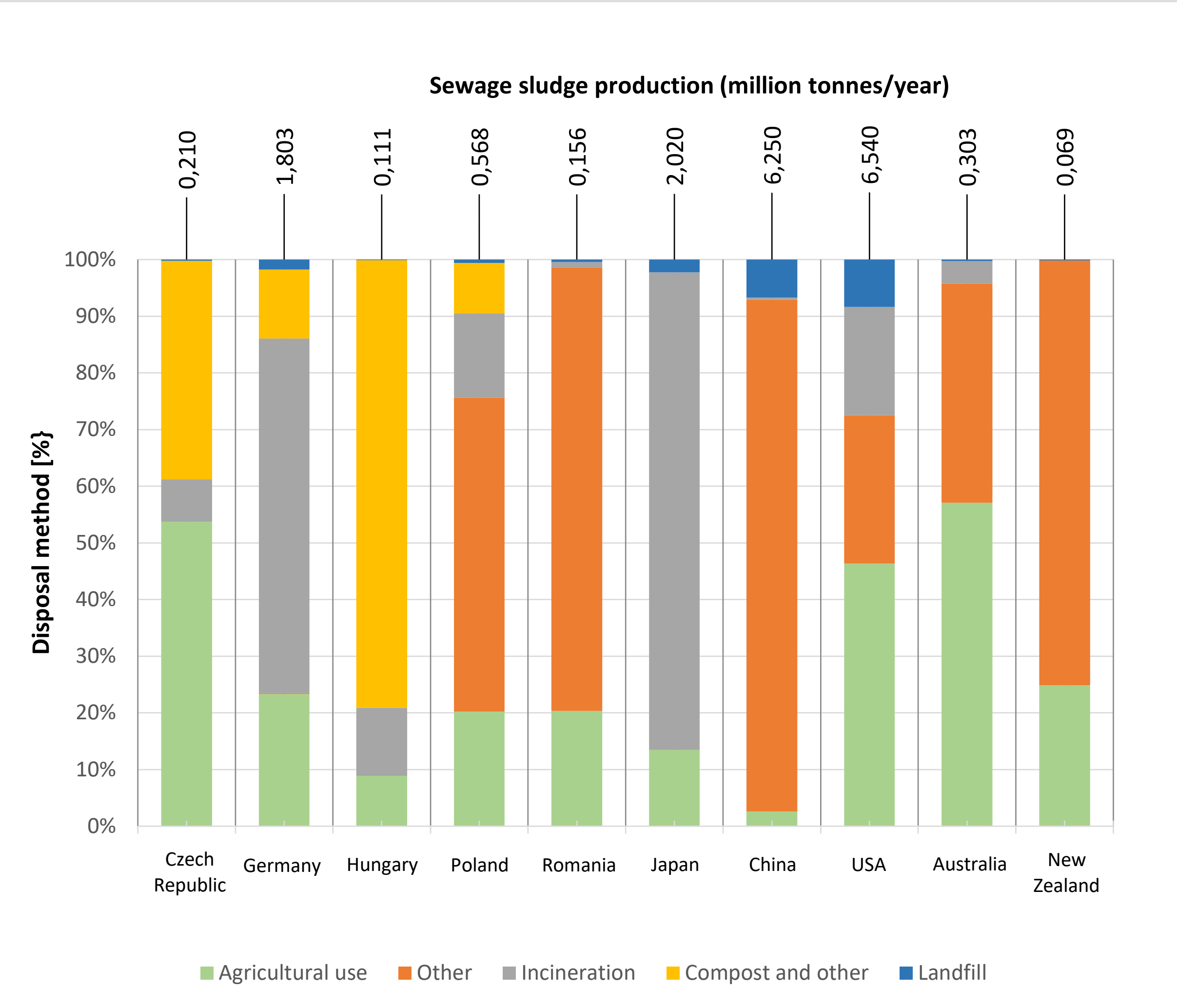

Figure 1. Worldwide implemented excess sewage sludge utilization methods (Christodoulou and Stamatelatou, 2016; Drechsel et al., 2015; Eurostat, 2015; Yang et al., 2015)

One of the industries in which waste materials can be used is the construction industry, which plays a significant role both in developing and developed countries. Pro-environmental action and sustainable construction practices, as well as an increasing demand for cement, are the factors which contribute to the use of waste materials in this industry, coming from construction and other industries, e.g. ashes from biomass incineration, blast furnace slag, gangue, sewage sludge and ashes after its thermal utilization, waste glass or materials after demolition of buildings (Smol et al., 2015; Supino et al., 2016). The use of sewage sludge in mortars or construction materials eliminates some of the expensive and energy-intensive stages of their disposal. In addition, environmentally harmful waste is transformed into a safe and stable product. The use of sewage sludge in mortars or construction materials eliminates some of the expensive and energy-intensive stages of its disposal. In addition, environmentally harmful waste is transformed into a safe and stable product.

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

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

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

The main purpose of the article is to present the latest methods of using non-ash sewage sludge in building and construction materials. The methods of using raw (unprocessed), stabilized (e.g. with lime) or dried sludge as additives to concrete mortars, cement slurries, construction products (e.g. blocks) and sintered/ceramic materials are presented. In addition, several examples are described of the production of low strength materials intended mainly for landfill applications and soil reinforcement. This publication does not contain information on the use of ashes obtained after thermal utilization of sewage sludge, because the implementation of such methods requires the construction of a thermal treatment plant, which inevitably involves considerable financial outlays. In addition, thermal treatment of sludge seems economically justifiable only for large wastewater treatment plants, e.g. those collecting sewage sludge from agglomerations over 200.000 inhabitants. The production of building materials from non-incinerated sludge may be an alternative for smaller sewage treatment plants, whose operators are struggling with the problem of managing excess sewage sludge.

2. Methods

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

3. Physicochemical characteristics of excess sludge

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

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

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

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

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

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

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

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

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

Source* \ *Element		***Cu* mg/kg DM**	***Zn* mg/kg DM**	***Pb* mg/kg DM**	***Cd* mg/kg DM**	***Ni* mg/kg DM**	***Cr* mg/kg DM**	***Reference***
Household wastewater		213	750	52	2.0	30	117	(Cheng et al., 2014)
Industrial wastewater		2.5	1.3	59	2.8	106	111	
Activated sludge	France	149	548	18	0.6	26.4	27.6	(Tella et al., 2013)
	Senegal	200	930	62	2.0	44	120	
Municipal sewage sludge		433	2032	126	2.78	621	856	(Ščančar et al., 2000)
Sewage sludge		2.6-131.2	28-2436	0.4-194.0	0.08-16	0.4-25	2.8-2855	(Często chowa University of Technology, 2004)
Municipal sewage sludge	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	
Sewage sludge		57	211	171	-	15	325	(Mulchandani and Westerhoff, 2016)
Municipal sewage sludge	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)

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

4. The main methods of excess sludge management

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

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

4.1. Agricultural use and biological utilization

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

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

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

Methane fermentation is also a biological process, but it takes place under anaerobic conditions. Anaerobic bacteria decompose biodegradable substances while producing biogas. Biogas (a mixture of mainly CH_4 and CO_2) shows a high calorific value and can be used to produce heat or electricity (Cao and Pawłowski, 2012).

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

4.1. Thermal utilisation methods

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

Combustion of excessive sewage sludge is becoming an increasingly used method of utilization. Considering the restrictions related to landfilling and use in agriculture, it is becoming more and more important mainly due to the disposal cost. The mechanism of sludge combustion differs from the mechanism of coal combustion, mainly due to the significant hydration of the substrate, mineral content and volatile fraction in the combustible substance (Środa et al., 2015, 2012). Combustion is most commonly carried out in fluidized bed reactors at a temperature of about 700 °C. The calorific value of dried sewage sludge is in the range of 12-20 MJ/kg, which is lower than the calorific value of coal but equivalent to the value for brown coal. Due to combustion, the volume of the sludge decreases by approximately 95 % and its mass is reduced to 1 % compared to the state before the process. Although ashes formed after combustion are a sterile and inert product, the elevated amount of heavy metals is the reason why they can be treated as hazardous waste (Środa et al., 2012; Tashima et al., 2017). There are known cases when volume reduction reached only approx. 90 %.

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

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

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

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

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

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

The main component of cements is clinker, a mixture of four main oxides: CaO, SiO_2, Al_2O_3 and Fe_2O_3, which comprises 95 % of its mass. As a result of thermochemical reactions between components of cement-based materials, the basic phases are obtained: tricalcium silicate, dicalcium silicate, aluminates and calcium aluminoferrites (Peukert, 2000). The evelopment of structure in a cement slurry consists of three stages. In the first stage, the sodium hydroxide present in the slurry solution separates into a solid form. Calcium sulphate simultaneously passes into the solution, reacting with the present minerals, leading to the formation of sulphoaluminates and calcium sulphoferrates. The hydration process of aluminates is slowed down due to the formation of the two aforementioned minerals on their particles. In the second stage, the C-S-H phase (hydrated aluminosilicates) is created, which fills in the open spaces and together with ettringite (hydrated calcium sulphoaluminate) they form a compact structure. In the third stage, pores in the slurry are filled with short-fiber and lamellar C-S-H phases, which can take several months. The hardened slurry therefore includes: C-S-H gel phase, crystalline materials (portlandite and ettringite), unhydrated cement grains, capillary spaces and pores (filled with water or air), and thin films of water inside the slurry (Peukert, 2000). The schematic process of hardening the cement slurry is shown in Figure 2.

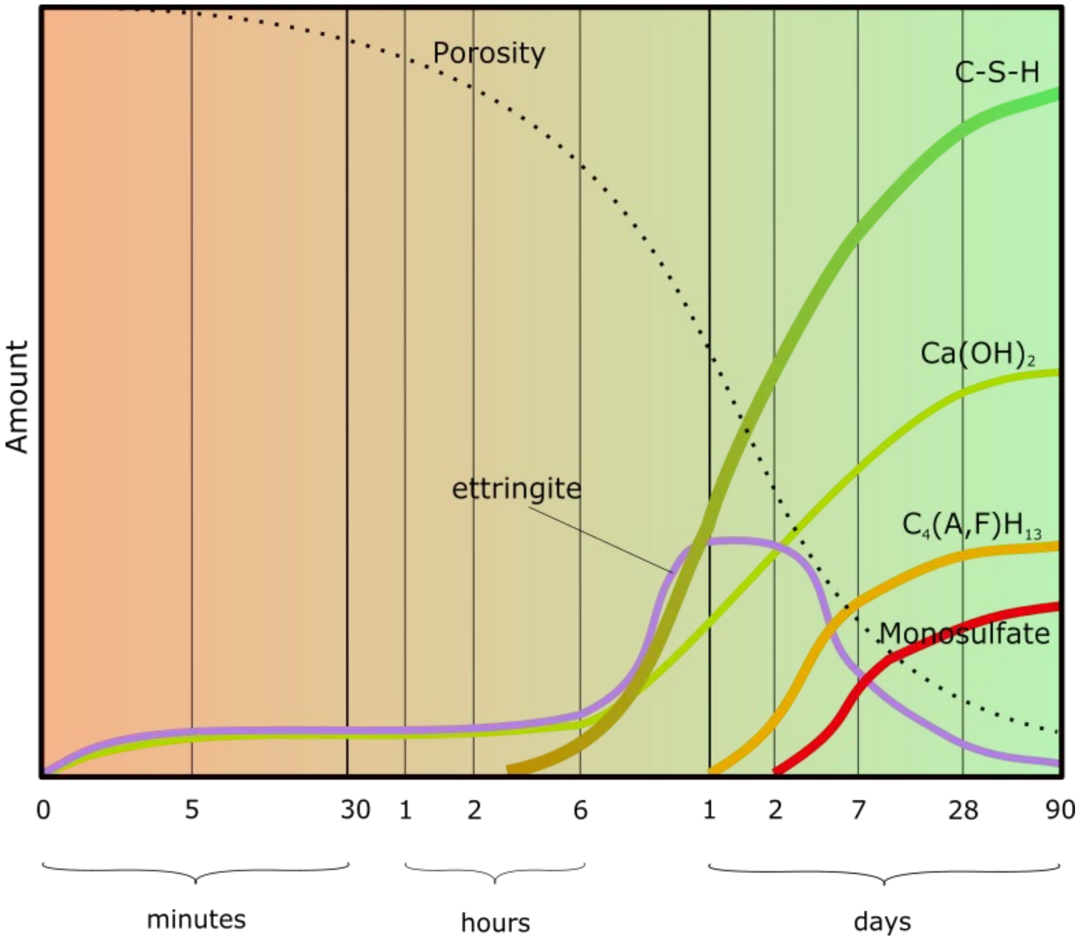

Figure. 2. Cement slurry binding scheme (Peukert, 2000)

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

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

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

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

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

Production of bricks, roof tiles and ceramic materials from raw materials intended for this purpose, as well as excess sewage sludge, is based on the sintering process, which is possible due to the presence of similar elements, such as in clay. During sintering, complex physical and chemical processes depend on the parameters of the process being carried out. Sintering, in contrast to vitrification, consists in pre-compacting the fragmented material and then heating the moulding at a temperature not exceeding the melting point of the ingredients. The thus obtained sinter is cohesive and more durable than a moulding. If a mixture of materials differing in the melting point is used, sintering is carried out at a temperature above the melting point of at least one component. Heating the powdered or fine-grained components of the mixture without bringing it to a liquid state causes the surface of the particles to begin to melt, thanks to which the grains merge into a porous element (Pater, 2014; Wiśniewski et al., 2012).

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

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

6. The use of undewatered, stabilized and dryed excess sewage sludge

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

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

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

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

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

On the basis of a mineralogical analysis of sewage sludge, a low content of mineral fraction was indicated, while the ashes from recycled paper contained mainly calcite. The leachates from the sample after 28 days of hardening were characterized by high pH, and heavy metal concentrations were lower than in the case of leachates from raw sludge and did not exceed the legal norms. The only exception was copper, the concentration of which in the leachates was higher than that of the other metals, but it did not exceed the standards that building materials applications must meet. Copper mobility is lowest in weakly alkaline solutions, while in strongly alkaline solutions it can increase. The authors indicate that according to the Slovenian law, the composite is suitable both for landfill capping and lining. Immobilization of heavy metals in the material enables its use in building embankments or road foundations. In addition to limiting leaching of heavy metals from sludge, an additional advantage of this solution is the fact that sludge does not require dewatering, which is associated with energy saving (Mladenovič et al., 2017).

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

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

In the work by Hwang et al. (Hwang et al., 2017), excess sewage sludge was used as a component of controlled low-strength material (CLSM). It is a cement liquid material capable of self-compacting, used to fill hard to reach places. In this case, the binders were fly ash from one of the Taiwanese heat plants and granulated blast-furnace slag from a steel factory, which were activated in the mixture with NaOH solution. The main components of the ashes were SiO_2 – 64 % and Al_2O_3 – 20 %. The ones of the blast furnace slag were SiO_2 – 39 % and CaO – 37.5 %. The tested mixtures were prepared by mixing fly ash with slag in a 7:3 ratio together with dried sludge in amounts of 10 % and 20 % in relation to the mixture of binders. The effect on the mixtures of different amounts of activator and water needed to make the samples was also checked. The mixtures were analysed after 1, 3, 7 and 28 days in terms of their compressive strength. The addition of sewage sludge negatively influenced the workability of the mass and extended its setting time in comparison with mixtures of the same composition, but without the participation of sludge. The influence of the addition of sewage sludge to the samples increased their water absorption, which contributed to increasing their compressive strength. The main microstructural phases in the obtained products were quartz and a matrix of calcium silicate hydrates (C-S-H).

Samples more abundant in sewage sludge were characterized by a denser structure which affected the compressive strength. The leachates from raw sediments and from the manufactured products were both characterized by very low concentrations of heavy metals (values of 0.01-0.05 mg/l) and, as a consequence, met the requirements of the Taiwanese Environmental Protection Agency. The sample containing 10 % sewage sludge and 9 % activator (presented as Na_2O) in relation to the binders was characterized by the best strength parameters. In addition, its physicochemical properties met the standards of the Taiwanese Department of Public Works. In the hardened materials only Cu and Zn (0.05 mg / L and 0.05 mg / L) were able to be determined, whereas concentrations of metals such as Pb, Cr, Ni were below the limit of detection (0.005 mg / L). The values provided by the regulatory limits for metals such as Pb, Cr or Cu must be below: 5.0, 5.0, 15.0 mg / L.

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

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

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

6.3. Stabilization of unprocessed sludge using Portland cement and additives

Unprocessed, raw sludge is highly hydrated. This property was used in the production of concretes and mortars, by completely or partially replacing raw sewage sludge with water in the mixtures (Hamood et al., 2017; Roccaro et al., 2015). The publication by Roccaro et al. presents results of testing concrete mortar samples in which water was replaced with aerobically and anaerobically stabilized sewage sludge in amounts ranging from 10 to 100 %. Compressive strength of the control sample containing no sewage sludge was 44 MPa. Replacing water with aerobically stabilized sludge in the amount of 10 %, caused the strength of the concrete sample to decrease to 39 MPa. It was shown that the excess sludge can partially or completely replace water in concrete mortar, however replacing the water with sludge even in the amount of 10 % reduces the compressive strength of the obtained materials (Roccaro et al., 2015). In addition to replacing water with sewage sludge, the mortar properties were additionally tested, where the cement was replaced by ash from coal combustion (Hamood et al., 2017). The ash had a high content of unburned carbon and large-sized particles, which is why it has not found its use in conventional construction. The sewage sludge used in the research (with the hydration of 97.5 %) came from a municipal sewage treatment plant. In order to remove pathogens, it was stabilized with lime (the pH of the sludge was lower than 12). Standard Portland cement CEM I was used to make mortars. The ash consisted mainly of SiO_2 (45.1 %), Al_2O_3 (16.9 %), Fe_2O_3 (9.0 %), and CaO (2.0 %). The cement binder in mortar samples was replaced by ash in amounts of 10 to 30 %. One group of samples was made using water (the reference samples), the other group using undewatered sewage sludge. The fluidity of mortars produced on the basis of 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 compared to the control sample. In the case of mortar samples, substitution of sand with sludge decreases their strength. After replacing 25 wt % of sand with sludge, the compressive strength decreases by 25 % (to 20 MPa), while the 50 % addition causes a 45 % strength reduction. Replacing sand with sludge in concrete mixtures in the amount of 15 % causes a reduction of their compressive strength from 24 MPa to 15 MPa. After 28 days of curing, samples of mortars and concretes were kept in water for 60 days in order to a test them for heavy metal leaching. Because the sludge particles were enclosed in a cement matrix, the leaching of heavy metals from the samples was minimal. The authors of the paper presented the results of research on Cr and Cd leaching from finished products. The concentration of Cd found to be below the limit of quantification and also lower than those required for inland surface water (0.01 mg/L). The permissible concentration of Cr set by the Department of Environment in Bangladesh was 0.5 mg/L. Only in this case the determined concentration turned out to be slightly higher than the normative value (0.73 mg/L) which was directly affect by the type of sewage sludge used, because it came from the textile industry and had a high concentration of Cd. Due to the low strength parameters, mixtures of mortars and concretes can be used in construction only where low durability is allowed (Rahman et al., 2017).

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

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

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

An attempt was made to utilize municipal sewage sludge by including it in the mass destined for the production of floor tiles (Amin et al., 2017). The sludge was dried, ground and added to the basic mix. The blend was moistened with water (5 %) and compressed at 30 MPa to obtain the desired shape of the product. After drying, the tiles were fired at temperatures from 1050 °C to 1150 °C. The share of sewage sludge in the total mass of the mixture ranged from 0 to 35 %. The main oxides included in the mixture used for the production of floor tiles were SiO_2 (58.53 %), Al_2O_3 (22.97 %), Fe_2O_3 (3.68 %) and CaO (1.34 %). In the sewage sludge, SiO_2 (9.46 %), Al_2O_3 (2.62 %) and P_2O_5 (3.81 %) predominated. The presence of sludge in the mixture causes the formation of open pores as a result of the oxidation of organic matter, which, along with the increasing content of sludge in the mixture, increases the water absorption capability of finished products. In order to comply with the standards that must be met by floor tiles, the content of sewage sludge in tile mixes should not exceed 15 %. Also, tiles should be fired at 1150 °C, ensuring that the water absorption value reaches 10 %. The addition of 5 % of sewage sludge lowered the flexural strength (modulus of rupture) of tiles fired at 1150 °C from approx. 29 MPa to 23 MPa. At the same time, a 10 % addition caused a drop to a value of around 18 MPa. According to ISO 13006/2012, which the authors refer to, tiles containing 5 %, 7 %, and 10 % of sludge, fired at 1100 °C, 1150 °C, 1150 °C respectively, can be used.

The production of bricks with the addition of sewage sludge is becoming a topic of interest for scientists. In the work by Zhang et al. (Zhang et al., 2016), the object of study were bricks made with lake sediments, slag and sewage sludge. All of the components were dried and ground to a particle size of < 2 mm. After adding an appropriate amount of water, bricks were formed and fired at 950 °C. In each of the used materials, there were oxides such as: SiO_2, Al_2O_3, Fe_2O_3 and CaO, the last two having the highest concentration in sediments. During the firing of bricks containing sludge, the additional heat resulting from the oxidation of organic matter melted the components of the mixture together. This influenced the number of open pores in the final product, and thus, the ability to absorb water was lower than in the case of the mixture of lake sediments with slag. The presence of closed pores also reduced the thermal conductivity of bricks (0.533 W/m·K) compared to samples without sludge. Compressive strength of a brick containing 5 % sewage sludge, 85 % of lake sediments and 10 % slag was lower by 38 % compared to a mixture without sludge (only lake sediment and slag). The compressive strength of this sample, 20.5 MPa, was in line with Chinese strength standards. Sewage sludge can be used in mixtures for the production of bricks, which is a modern form of utilization. Their presence in the mixture ensures that the bricks shrink less during the process of drying before firing and the finished products better insulate heat. On the other hand, the compressive strength and frost resistance of the obtained products is lowered (Zhang et al., 2016).

In the study by Kadir et al. (Kadir et al., 2017) clay was used as the main component of the mixture instead of lake sediments. Both raw materials – clay and sewage sludge – were dried. The proportion of sludge in bricks ranged from 0 to 20 %. The bricks were fired at 1050 °C. The composition of oxides contained in both clay and sludge was similar. Mainly SiO_2, Al_2O_3 and Fe_2O_3 were determined. In contrast to clay, sewage sludge was characterized by a high P_2O_5 content (approx. 7 %). It was noted that the higher the content of sewage sludge in the mixture, the more the samples shrink during firing. The authors add that bricks of good quality should have a maximum shrinkage value of 8 %. For the tested bricks, the shrinkage value was lower than the mentioned 8 %. Increasing the share of sewage sludge in the mixture also affects the density of bricks, which decreases with the increasing content of sediments due to the high content of organic matter. Water absorption, similarly as in the aforementioned research, increases together with the content of sediments. Bricks without the addition of sewage sludge reached a compressive strength of approx. 27 MPa. The addition of only 5 % of sludge caused a drop in strength to 12.6 MPa. This decrease is related to the formation of pores in finished products as well as lower sintering temperature compared to the previous tests (Zhang et al., 2016). The authors indicate that the use of sewage sludge for the production of bricks may be an alternative method of its utilization, however its excessive addition (20 %) causes a significant weakening of the manufactured products. The share of 5 % sewage sludge in the mixture qualifies the obtained bricks as high-strength materials (Kadir et al., 2017).

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

The work by Ukwatta et al. (Ukwatta et al., 2015b) presents the use of biosolid in fired bricks. In the studies, the authors used standard brick soil and biosolids, which came from 12-year-old stockpiles. Prior to testing, all samples were dried before adding them to the brick mass. The proportion of biosolids in bricks was 25 % of the mixture before firing. In parallel, a series samples were prepared without the participation of biosolids. The process of making bricks consisted in wetting the mass to approx. 20 %, pressing it to the appropriate size and drying it in the air for 24 hours. Then the prepared bricks were fired in a temperature of 1100 °C for 3 hours. The elemental composition of the bricks obtained was similar. The main oxides found in the bricks were SiO_2, Al_2O_3 and Fe_2O_3. The content of most oxides in bricks with the addition of biosolids was comparable to the control sample. Differences were observed only in the case of P_2O_5, which was nearly 4 times more than in the control sample. The compressive strength value of bricks with the addition of biosolids ranged from 25.9 to 16.2 MPa. In the case of a control sample, this value was 36.1 MPa. The reduction in strength is related to the higher porosity of the bricks obtained in relation to the control sample. Bricks with a 25 % share of bioslolids were characterized by lower density, lower thermal conductivity and higher porosity, which was caused by the burning out of organic matter. The obtained bricks, despite the reduced compressive strength in relation to the control sample, were more durable than the required strength value in the Australian Standards (3 MPa) (Ukwatta et al., 2015b).

The same authors in another paper (Ukwatta et al., 2015a) also presented the influence of the percentage of biosolids on the properties of bricks produced. The materials used in the research were the same substrates as in the work (Ukwatta et al., 2015b). Samples contained from 5 % to 50 % biosolids, while the control sample was made of bricks without biosolids. In the case of this work, the authors fired samples at a lower temperature, which was 1020 °C. Finished products have absorbed less water than expected by Australian standards. The dependence was found that along with the increase in the proportion of biosolids in bricks, the water absorption increases. The addition of up to 50 % biosolids caused a drop in the compressive strength value of fired bricks by 40 %. Nevertheless the value was higher than predicted by the Australian Standards. Therefore, the concentration of Cu in bricks containing biosolids ranged from 0,025 to 0,030 mg/L, while Australian Standards required 200 mg/L. In addition, the presence of significant amounts of organic matter in bricks allows to reduce the energy demand during firing bricks. The results of studies on the possibility of leaching heavy metals from bricks containing biosolides proved to be much lower than acceptable regulatory limits. According to the authors, you can successfully use bricks, in which the content of biosolids is not more than 50 %, because such bricks are characterized by high quality and good mechanical and physical properties (Ukwatta et al., 2015a).

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

The work by Mozo and Gómez (Mozo and Gómez, 2016) presents the results of research on the properties of bricks containing standard clay for making bricks and biosolids in an amount of 5 to 15 % of biosolids. The control sample consisted of bricks without their addition. Due to the fact that the properties of the final products are influenced by the particle size of the used substrates, all raw materials have been ground to a particle size from 70 μm to 1 mm. The formed bricks were fired at different temperatures: 950 °C, 1000 °C and 1050 °C. Both raw materials were characterized by a high content of quartz. The presence of gibbsite and calcite in biosolids makes using them in brick mass a good solution. According to Colombian requirements for compressive strength of bricks (NTC 4205), this value for nonstructural masonry units is 14 MPa, while for structural masonry units it is 20 MPa. As in other works, the compressive strength of bricks decreases with the participation of biosolids and lowering the sintering temperature. The control sample had a compressive strength of 34.05 MPa at 1050 °C and a 5 % share of biosolids in bricks resulted in a drop in strength to 23.8 MPa. According to the authors of the work, the presence of biosolids minimizes the risk of occurrence of deformations and cracks during the drying process. Bricks with only 5 % content of biosolids fired in 1050 degrees meet the mentioned standards. The authors did not present information on the leaching of heavy metals from bricks in their work (Mozo and Gómez, 2016).

6.5. Production of concretes with lightweight aggregate from sewage sludge

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

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

The materials used for the production of lightweight aggregate in the work presented by Franus et al. (Franus et al., 2016) were mechanically dewatered sludge (part of the wastewater came from industry) and clay. Both substrates were dried and ground to a particle diameter of less than 0.5 mm. As in the case of the research results presented in the article by Suchorab et al. (Suchorab et al., 2016), the amount of dried sludge in the clay mixture was 10 % (by weight). The balls formed from the mixture were dried and fired for 30 min at 1100 and 1150 °C. The physical properties of the obtained aggregates did not differ significantly from similar aggregates of commercial origin. Aggregates produced at higher temperatures showed higher porosity due to the production of gases as a result of the decomposition of organic matter, but nevertheless met the requirements for water absorption. Compressive strength of the aggregate fired at 1100 °C degrees was nearly six times higher (4.64 MPa) than the aggregate fired at 1150 °C. This is due to the presence of a glassy film and a higher number of pores in the aggregate fired at higher temperatures. An analysis of leachates showed that sintering of sludge into lightweight aggregates prevents the heavy metals contained in them from leaching. This is caused by the presence of calcium, sodium and magnesium aluminosilicates in the clay, which have the capacity for heavy metal sorption. Both of the obtained aggregates can be used as additives to concretes used in the insulation of floors or ceilings, or for the construction of curtain walls (Franus et al., 2016).

For the production of lightweight aggregate, two waste materials can be used simultaneously – glass and sludge from sewage treatment plants (Tuan et al., 2013). The study used wet sludge containing 70-80 % moisture. The waste glass was pre-dried and ground in a ball mill to particles smaller than 150 μm. The proportion of sewage sludge in the mixtures ranged from 50 to 90 %. Depending on the composition, the aggregates were fired at temperatures of 830 to 1100 °C. Due to its best properties, an aggregate made of 70 % sludge and 30 % glass (fired at 970 °C) was used in the concrete. The control sample was a concrete with a natural coarse aggregate. Apart from the mentioned aggregates, the concrete also consisted of: sand, ash and a plasticizer. The main oxides occurring in sludge included: SiO_2, Al_2O_3, Fe_2O_3, CaO as well as P_2O_5, which constituted as much as 15 %. In the case of glass waste, the main oxides were SiO_2, Al_2O_3 and CaO. The addition of waste glass can reduce the sintering temperature due to the presence of Na_2O in it, which translates into energy savings. Water absorption decreases when the sintering temperature rises, similarly to when there is more waste glass in the sample. The sintering temperature is also important, because, for example, a blend with 30 % glass content becomes more porous when the sintering temperature increases. When sintering the mixture at a temperature of 900-970 °C, it swells and the coating melts, thanks to which the pores are closed. Increasing the temperature further causes the pores to start to collapse. The strength of aggregates depends mainly on their composition, in general the more waste glass in the mixture, the higher the compressive strength of aggregates. Concrete with the addition of aggregates with a content of 70 % of sludge and 30 % waste glass, sintered at 970 °C, can be considered a good quality building material. After 28 days it had a compressive strength of 49.46 MPa, which meets the strength requirements in accordance with ASTM C330 and ACI 318 for structural concretes (the standard is 17.2 MPa) (Tuan et al., 2013).

The work by Lau et al. (Lau et al., 2017) presents the method of producing lightweight aggregates from lime-stabilized sewage sludge and ash after palm oil combustion. As mentioned in the paper by Tuan et al. (Tuan et al., 2013), glass waste has a high content of Na2O, which reduces the sintering temperature. The use of sodium silicate in the mixture yields a similar effect. Mixtures of sewage sludge, ash after palm oil combustion and sodium silicate were sintered at three different temperatures: 1160, 1180 and 1200 °C. The main oxide present in the sewage sludge (probably due to its stabilization) was calcium oxide (41.53 %), while in the ash it was SiO_2 (59.13 %). The sewage sludge and ashes were dried and ground to a fine powder. Both substrates were sieved to obtain particles smaller than 150 μm. The percentage of sludge used ranged from 40 % to 60 %. Three series of tests were carried out. In the first two, 10 and 15 % of sodium silicate was added to the ash and sludge mixtures, respectively. The last series did not contain sodium silicate. It was shown that the higher the ash content in the mixture, the higher the density of the fired aggregates. Due to the fact that the ash after palm oil combustion had a lower melting point, it filled the spaces between the remaining particles when melting. In the samples without the addition of sodium silicate, the aggregates had high porosity and low bulk density, which resulted in an increase in the water absorption capability and reduced the compressive strength. The addition of a silicate affected the strength of the aggregate, which increased together with its content. Aggregates with a content of 40 and 50 % of sludge with a 15 % addition of silicate, fired at 1160 °C, had a compressive strength of 8.1 and 7.4 MPa, respectively. Such values of compressive strength and density of aggregates qualify them as lightweight aggregates (bulk density below 1200 kg/m3 – in accordance with BS EN 13055) (Lau et al., 2017). For the purpose of summarizing, all materials containing sewage sludge which can be used in the construction industry are listed in Table 2. For a better comparison of material properties, the table also includes compressive strength values for samples with the most optimal composition (in terms of properties and strength).

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**
Material for covering landfill sites	-	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)
Controlled low-strength material (CLSM)	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			

Concrete	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)
Mortar	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 22.5 25 25	1.25 2.5 7.5 18.75	Dried sewage sludge from the textile industry	Sand	Approx. 23 Approx. 14 Approx. 25 Approx. 20	Low-strength construction materials	Substituting cement with sludge Substituting sand with sludge The calculations did not take into account the weight of water needed for mortar preparation	(Rahman et al., 2017)

Bricks/concrete blocks	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)
Sintered products	95 90 95	5 10 5	Dried sewage sludge from a municipal sewage treatment plant	A standard mixture for the production of tiles	23* 18* 17*	Floor tiles in accordance with ISO 13006/2012	Firing temperature: 1150°C 1150°C 1100°C * - Flexural strength	(Amin et al., 2017)
	95	5	Dried sewage sludge	85% lake sediments, 10% slag	20.5	Bricks	Firing temperature 950°C	(Zhang et al., 2016)
	99 95	1 5	Dried sewage sludge	Clay	22.3 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)
Lightweight aggregate	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)

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 form produced construction materials while they are embedded in the matrix. Even if heavy metals are leached form 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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