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USE OF SEWAGE SLUDGE ASH IN CEMENTITIOUS MATERIALS

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Abstract. The potential for using sewage sludge ash (SSA) in cement mortars and concrete is reviewed. The chemical and physical properties and pozzolanic activity of a range of different incinerated SSA samples indicates the potential to exploit the pozzolanic properties of this waste as a supplementary cementitious material (SCM). Using SSA as a SCM increases the water demand and reduces the workability, compressive strength and density of concrete mixes, although these adverse effects may be controlled by modifying the mix design. This represents a beneficial reuse application for a waste that is typically landfilled. However the use of SSA in cementitious materials must be carefully controlled because SSA varies significantly, depending on sludge production method and combustion conditions. Testing will therefore always be required to assess how a specific SSA behaves when incorporated in cementitious materials.

1. INTRODUCTION

The treatment of wastewater and management of process by-products is now a major global issue. Wastewater treatment plants (WWTP) are producing increasing quantities of sewage sludge and this requires careful management. Sewage sludge is a by-product from physical (sedimentation), biological (microbiological activity) and chemical (coagulation, flocculation) processes and is a complex mix of organic and inorganic substances that typically contains pathogenic microorganisms, parasites, viruses and numerous potentially toxic elements and compounds, including heavy metals. The number of WWTP is increasing, particularly in developing countries, and therefore sludge production is also increasing [1]. Data on the annual production of sludge from WWTP in the EU is given in Fig. 1. The EU is expected to produce ~13 million tonnes of sludge dry matter (DM) per annum by 2020 [2,3].

The efficiency and cost of WWTP expressed per unit of population equivalent (PE) cannot be based on just the costs associated with the WWTP, but must include the final sludge disposal costs. Sewage sludge must be managed in accordance with relevant legislation and sludge treatment and disposal costs can be significant. For a WWTP with a capacity between 5,000 and 200,000 PE sludge disposal is estimated to be ~50% of total operating costs [4] and in some circumstances when, for example, long transport distance to disposal sites are involved, the cost can be significantly higher.

The EU Directive 91/271/EEC requires that sludge management involves efficient recycling of

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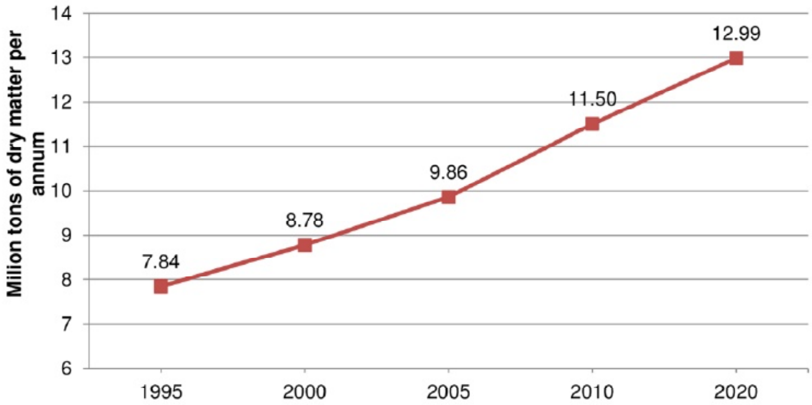

Fig. 1. Estimate of the increase in annual production of sludge from WWTP within the EU, data replotted from [2].

resources without influencing public health or contaminating the environment. Prior to 1998 sewage sludge could be disposed of in the sea [5]. The main options for sludge disposal are now landfill [6], agricultural use to improve soil, sludge drying and incineration.

Sludge drying plants are operating in some EU regions [7]. These reduce sludge volume and produce a biologically stable, odourless product. Considerable energy is required to dry sludge, typically 8,293 J/g or 1,990 kcal/kg, and the dried sludge produced is a potential renewable low-carbon biomass fuel. Dried sewage sludge has considerable calorific value and has been assessed for use as an alternative fuel for cement production. In this case the ash remaining from sludge combustion is incorporated into cement clinker, substituting part of the raw materials used in cement production [7-9].

Incineration of dewatered sludge reduces the total mass by ~85% [10] and volume by up to 90% for dewatered sludge with 20% dry mass (DM). The combustion process destroys hazardous organic components in the sludge and minimises unpleasant odours, but requires further sewage sludge ash (SSA) management [11]. Recent estimates are that annual global production of SSA is ~1.7 million tonnes and this is expected to increase in the future [12]. The majority of SSA generated worldwide is currently landfilled.

The construction industry is an important consumer of natural resources and materials, and has significant potential to use selected wastes generated by other industrial sectors. The use of wastes in construction can conserve non-renewable resources, make products more cost competitive and reduce the amount of waste disposed of to landfill. However, although industrial waste materials may be incorporated in cementitious materials by various methods, the proportion used are typically low, normally less than about 20% to avoid undesirable effects on the final product [13].

There is significant potential for SSA to be used in concrete although the conditions, methods and quantities that can be substituted depend on a number of factors [14]. SSA may be used in cementitious materials as a pozzolanic material, partly substituting for cement or as a filler replacing or partly replacing sand. Numerous studies, some of which are older, have investigated the use of SSA in cement mortars [15,16] and concrete [17,18]. This paper reviews the advantageous and deleterious effects of SSA on cementitious materials.

2. CHARACTERISTICS OF SSA

SSA is formed from the ~30% by mass of inorganic matter present in sewage sludge. This produces a fine powder on combustion that may contain some sand-sized particles, with negligible residual organic matter and low moisture [19]. Typical SSA particle size distribution data is shown in Fig. 2. The particles diameters range from 1 to 100 μm, with a mean of ~26 μm [20, 21]. A comparatively high percentage of particles, up to 90% in some cases, are smaller than 75 μm [21]. The particle size of SSA generated from combustion of sewage sludge produced in Croatia is also included in Fig. 2. The majority of particles (50 to 60% by mass) were in the range from 20 to 48 μm. The exact particle size range depends on the sludge treatment process, the percentage of industrial wastewater being treated and the type of the sewage sludge incineration system.

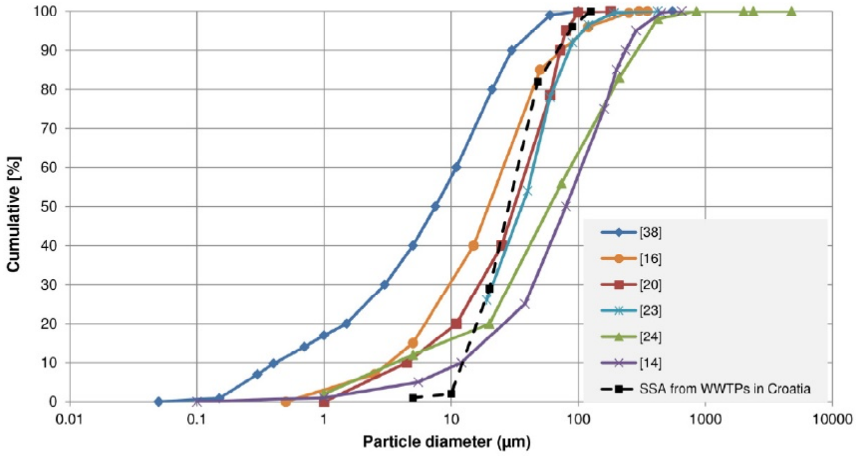

Fig. 2. Particle size distribution of SSA based on different reports.

SSA typically consists of irregular shaped porous particles with large specific area and high water uptake [22]. The specific gravity is typically in the range between 2.3 and 3.2 g/cm^3 [14,23,24] and SSA density has been found to increase with increasing incineration temperature from 2.67 g/cm^3 at 800 °C to 2.83 g/cm^3 at 1000 °C [25].

The major elements present in SSA are Si, Ca, Fe, Al, P, and O and the main crystalline phases present are quartz (SiO_2), calcium phosphate ($Ca_3(PO_4)_2$) and hematite (Fe_2O_3). SSA may also be amorphous when high temperature combustion is used [26].

SSA contains significant levels of phosphate, usually between 10 and 20% by mass. Phosphate levels were found to vary in SSA produced from WWTP in Croatia as shown in Table 1, Fig. 3. Phosphate can delay cement setting and usually reduces initial concrete strengths. There may also be significant concentrations of SO_3 [13] which result from the chemicals used in some wastewater treatment processes [27]. Leaching of Cr^{6+} from SSA is also a potential problem [28]. The type of wastewater and the additives used in the WWTP and in sludge treatment influence the composition of SSA [14,29]. Tertiary sludge treatment uses Fe and Al salts to precipitate phosphorus and this increases the concentration of these metals in SSA. Even when WWTP are operating under steady state conditions, the composition of major elements in sewage sludge and SSA can vary significantly [30,31]. The levels of trace elements are influenced by the type of industrial activity in the area serviced by the WWTP. Hg, Cd, Pb, Sb, and As tend to volatilize during combustion [32] but condense onto SSA particles when the temperature is reduced during the gas clean-up process. Leaching of Sb, Mo, and Se means that SSA may be unsuitable for disposal in inert waste landfill [13, 33].

Table 1 shows the composition of SSA generated by combustion of sewage sludge from the WWTP at Karlovac, Koprivnica, Zagreb, and Varazdin in Croatia. The variations are due the differences in wastewater and sludge treatment and combustion temperature (800 °C and 1000 °C). The Koprivnica WWTP uses MID-MIX® technology [34], and this produces a very different and unusual type of SSA.

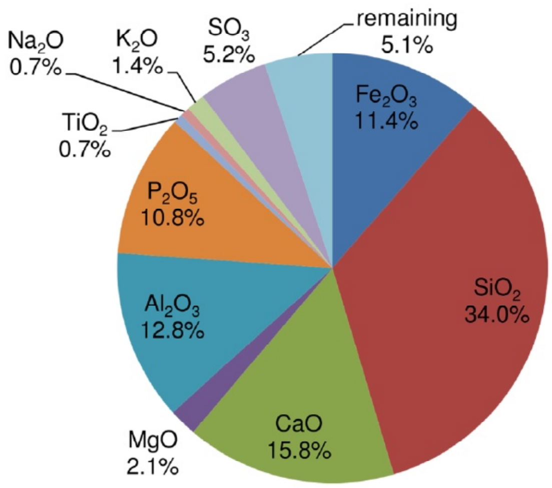

Fig. 3. Mean values of the composition of SSA in term of oxides (according to results of research listed in Table 1).

Table 1. Comparison of value ranges of some chemical compounds in SSA for various origins and sludge treatment methods [11,13,20,22-26,35-45].

			Composition of SSA [%]			
Oxide	Range according to previous research	Mean according to previous research	WWTP Karlovac (Croatia)-3rd stage of treatment (conventional sludge treatment)	WWTP Koprivnica (Croatia)-3rd stage of treatment (MID-MIX® sludge treatment)	WWTP Zagreb (Croatia)-2nd stage of treatment (conventional sludge treatment)	WWTP Varazdin (Croatia)-2nd stage of treatment (conventional sludge treatment)
Fe_2O_3	4.7 – 20.0	11.4	8.2 – 9.5	0.3 – 0.4	4.3 – 6.0	0.9 – 1.0
SiO_2	17.3 – 50.6	34.0	2.9 – 7.9	0.4 – 0.5	16.2 – 22.1	7.0 – 8.3
CaO	1.9 – 31.3	15.8	37.6 – 42.1	92.8 – 93.8	39.2 – 52.2	54.9 – 62.4
MgO	1.4 – 3.2	2.1	4.2 – 4.5	0.7 – 0.8	3.0 – 3.5	1.4 – 1.7
Al_2O_3	6.3 – 19.1	12.8	11.7 – 16.5	0.9 – 1.2	8.0 – 10.8	1.4 – 1.7
P_2O_5	1.7 – 18.2	10.8	16.0 – 17.2	0.8	5.2 – 7.5	10.3 – 12.0
TiO_2	0.3 – 1.0	0.7	0.8 – 1.0	0.0 – 1.0	0.8 – 1.0	0.1 – 0.0
Na_2O	0.3 – 1.3	0.7	0.3	0.0	0.1 – 0.2	0.2
K_2O	0.6 – 2.3	1.4	1.2 – 1.3	0.1	0.4 – 0.8	0.6

3. EFFECTS OF SSA ON CEMENTITIOUS MATERIALS

3.1. Use of SSA as a partial substitute for cement

3.1.1. Pozzolanic properties of SSA

The content of SiO_2 (17.27 - 50.60%) and Al_2O_3 (6.32 – 19.09%) in SSA, shown in Table 1, indicates that this material may be pozzolanic with potential to be used as a supplementary cementitious material (SCM). There are numerous direct and indirect methods for determining the pozzolanic activity of a material. To date, most research has used indirect methods, i.e. recording the effects of substituting part of the cement content by SSA on mortars and pastes on compressive strength. Adverse effects are attributed to increased water requirements due to the irregular morphology of SSA particles [12]. Using direct methods, Jamshidi et al. [1] determined the pozzolanic activity of SSA to be 37.86%, while Fontes et al. [38] derived a value of 70.53%.

Results by Pan et al. [42] indicated that the pozzolanic activity of SSA was proportional to the surface area. It was found that the strength activity index (SAI) increased by approximately 5% per additional 100 m^2/kg increase in fineness.

Increasing SSA particle fineness is reported to result in improved workability, longer setting time, higher absorption of water due to the larger free surface of particles, higher pozzolanic activity and consequently higher compressive strength [42]. Monzo et al. [40] also reports that SSA is a reactive material that contributes to the strength of cement mortars due to its pozzolanic characteristics.

3.1.2. Effect of SSA on mix workability

Problems reported when part of the cement in cement mortars is substituted by SSA are mainly associated with reduced workability, as shown in Figure 4, and higher water demand, which may be compensated for by using chemical additives such as plasticizers and superplasticizers. Monzo et al. [40] reported a non-linear fall in workability in cement mortars mixed with increasing SSA content with higher additions of SSA in cement mortar producing a reduced fall of workability per SSA increment (Fig. 4).

The high water demand of SSA is associated with the high porosity in SSA particles. Other mineral admixtures, such as fly ash, are known to have the opposite effect, and their use frequently leads to decreased water demand. Silica fume addition results in a high water demand, similar to SSA, due

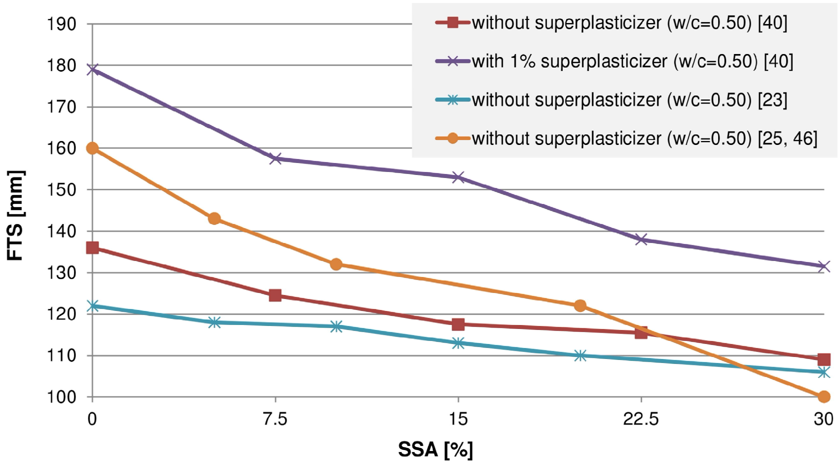

Fig. 4. Dependence of consistency on portion of SSA in cement mortar (FTS - flow table spread), data from [23,25,40,46].

to its very fine particle size [20]. The higher water demand observed at high SSA replacement ratios can lead to a decrease in the mechanical performance of samples unless superplasticizers are used to counteract this effect [22]. Vouk et al. [25] confirmed that workability decreased with increased SSA addition (an average decrease of workability was about 20% when 20% of cement was replaced by SSA), but also found that SSA produced at higher temperatures had a reduced effect on mortars workability. The least effects on workability were achieved using SSA produced by combustion at 1000 °C. The problems related to reduced workability may be solved in part by adding coal fly ash to mortars containing SSA [43]. This allows greater cement substitute by SSA, longer hydration time, and the synergistic effect of several materials with pozzolanic properties on the final product. The addition of 20% of fly ash compensated for the adverse effects occurring in cement mortars caused by adding 10% of SSA as substitute for cement.

The irregular morphology of SSA particles causes the reduction in the workability of mortar, even at low SSA additions. Poor workability may also be compensated for by increasing the fineness of ash particles [42] or by adding super-plasticizers [40]. The volume stability of mortars was not modified when SSA were used, and no expansion was observed with 10% SSA substitution of cement [23].

3.1.3. Effect of SSA on setting time

For SSA with a particle fineness of 500 m^2/kg the initial setting time of cement mortar with 20% SSA replacement was ~3 hours, while the final setting time was ~4 hours [21]. For comparison, initial and final setting times for Portland cement mortars are 2-4 hours, and 5-8 hours, respectively. When particle fineness was increased to 780-1000 m^2/kg, initial and final setting times of cement mortars with up to 30% of SSA were increased to 3.5-5 hours and 7-8 hours, respectively [47]. The conclusion is that setting times are longer for SSA particles with greater fineness. However Garces et al. [23] concluded that replacement of 10% of cement by SSA did not change the initial setting time and the end of the setting period was only slightly longer than the reference mixture. SSA produced by incineration at 1000 °C was found to have a greater impact on setting time than SSA incinerated at 800 °C [25]. These authors also found minimal influence of SSA addition level on setting time. The effect of SSA on the setting time is determined by the chemical composition. CaO, MgO, and chlorides accelerate setting, sulphates affect setting time and also strength development, while the phosphate content (in the form of P_2O_5) affects the end of setting at concentrations higher than 0.3% [48].

3.1.4. Effect of SSA on the mechanical properties of cementitious materials

SSAs are known to be sulphur-rich wastes [49] so the possibility of concrete degradation due to sulphate influence is a major consideration, although it does not have a decisive influence on strength development [21]. According to research by Fontes et al. [38], cement mortars in which 10-30% of cement was substituted with SSA showed approximately equal flexural 28-day strengths as reference mortars, while compressive strengths of reference mortars were achieved after shorter hydration time

Table 2. Compressive strength of hardened mortar with 20% SSA addition, data from [42].

Hydration time [days]	Control mixture compressive strength [MPa]	SSA mortar compressive strength [MPa]						
		SSA grinding time [min]						
		10	20	30	60	120	180	360
7	27.9	11.5	14.1	11.5	12.5	20.4	19.7	19.2
28	38.1	18.4	22.0	22.3	27.9	26.7	27.5	29.5

(up to 7 days). Partial substitution of cement by SSA in concrete contributes to an increase of total porosity.

SSA is particularly compatible with cements containing a large portion of C3A in cement mortars, and in this case deterioration of mechanical properties after 28 days hydration has not been recorded [21]. Table 2 shows the influence of the fineness of SSA on the mortar properties [42]. Increasing the fineness of SSA particles improves the compressive strength of samples with the same SSA content.

Still, comparing the results of individual authors, considerable differences of values may be noticed. For example, substitution of 20% of Portland cement by SSA results in different reductions of compressive strength: 24% [33], 52% [42], 32% [50]. Along with previously mentioned additional water demand in mortars with SSA (Section 3.3), reduced workability and longer setting time, Cyr et al. [22] also demonstrated that 28-day compressive and flexural strengths are reduced compared with ordinary mortar as shown in Fig. 5.

The work by Fontes et al. [38] analyzed the effect of substituting 10-30% of cement by SSA in mortars and high performance concretes, and the conclusion was that substitution from 5-10% meets all requirements regarding mechanical properties.

According to Chen et al. [14] compressive and flexural strengths of analyzed mortars decreased linearly with the increase of percentage of cement substitution by SSA. This effect is explained by: (i) the excessive water content which is required in mixtures with SSA to maintain workability and (ii) the CaO content in ash (less than 10%), which affects the hydraulic properties. According to this research, for mixtures with an SSA content of 10%, the recorded decrease of flexural and compressive strength was less than 25% in relation to control samples without SSA.

Results published by Monzo et al. [16,27,49] distinguish themselves from others, because they record moderate increase of compressive strengths of mortars with SSA in relation to control samples. They show average increase of strength of 8.3 - 15.3% when 15% of SSA is substituted for cement in mortars with the mixing ratio of 3:1. These samples are cured by immersion in water at 40 °C, and this moderately increased curing temperature is considered the reason for the different recorded results.

Garces et al. [23] found that cement CEM II/B-M (V-LL) was the most suitable (out of other commercially available types of cement that were analyzed) for making of mortars with various proportions of SSA. Mortars with SSA (10, 20, and 30%) had lower flexural strengths compared to mortars made with 100% of cement. In all mortars, compressive strength decreased as the proportion of SSA increased.

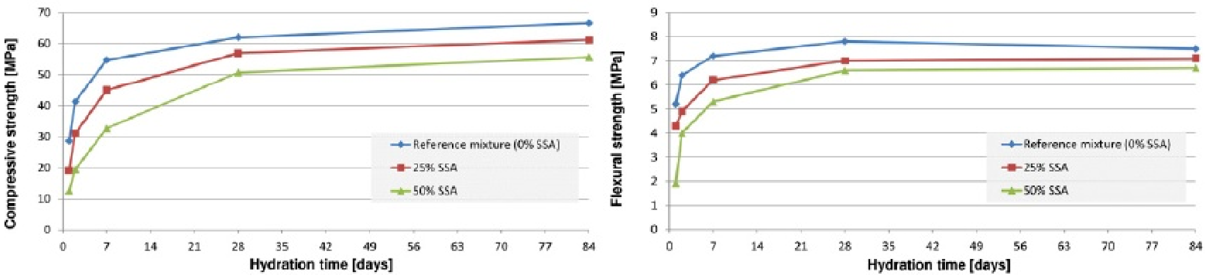

Fig. 5. Compressive and flexural strength of cement mortar with 0, 25% and 50% SSA, data from [22].

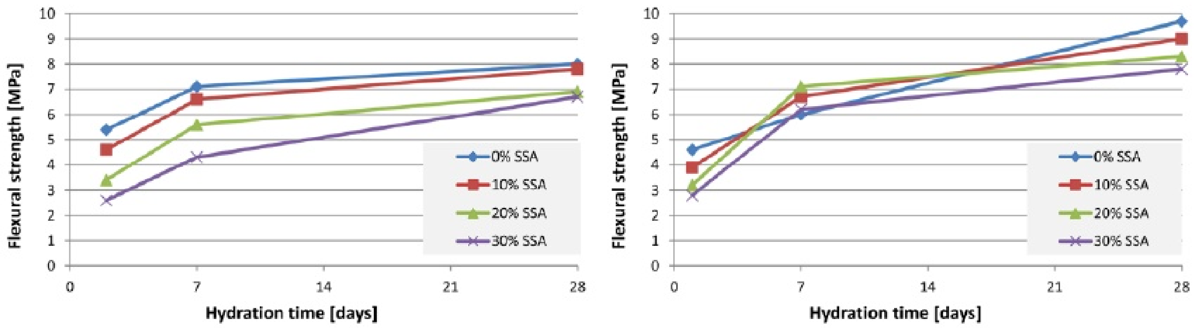

Fig. 6. Flexural strength of cement mortar with 0 – 30% SSA, data from: left [23]; right [25,46].

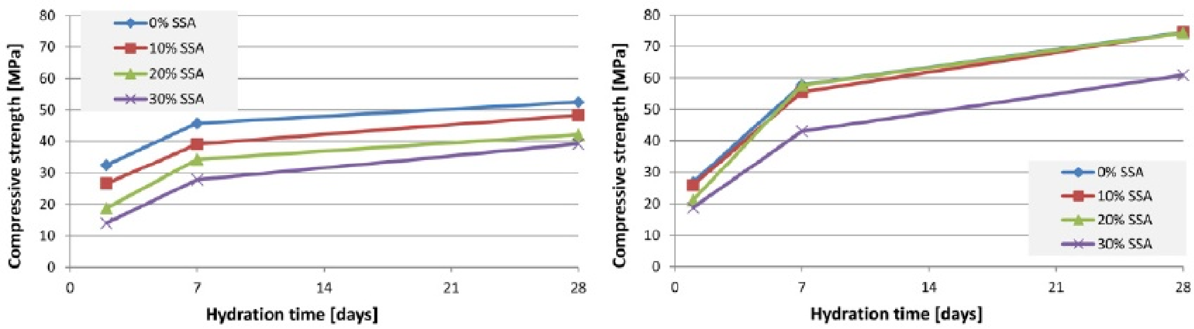

Fig. 7. Compressive strength of cement mortar with 0 – 30% SSA, data from: left [23]; right [25,46].

Vouk et al. [25,46] point out that mortar mixtures with up to 20% of SSA show similar, and in some cases even higher compressive and flexural strengths in comparison with reference mixtures. This research was conducted in similar conditions to those used by Garces et al. [23]. The main difference is that the SSA used by Vouk et al. was obtained by incinerating sewage sludge under laboratory conditions. Figs. 6 and 7 show a comparison of results of two studies (using SSA obtained at 800 C, cement CEM II/B-M (S-V) 42.5 N, and *w*/*c*=0.50).

According to research by Baeza-Brotons et al. [13], samples with SSA content substituted for up to 5% cement in concrete showed somewhat higher compressive strengths compared to reference samples. SSA contents above 5% result in somewhat lower values of compressive strength, but still higher than 90% of compressive strength of reference samples, while flexural strength always remained lower than the flexural strength of reference samples (between 71% and 85% of the reference value) [13]. These authors also recorded that with the addition of SSA water absorption of mortars increases, while it decreases for concrete (Fig. 8).

Perez-Carrion et al. [26] reported that precast concrete blocks containing 10% and 20% SSA exhibited 25% higher and 5% lower mean compressive strength, respectively, than the control.

Compressive strength of mortars made using SSA increases as the particle size of added SSA decreases. Improvements are due to the pozzolanic properties of SSA particles [33]. However, there is a considerable reduction of workability of such mortars due to the irregular shapes of SSA particles, as well as increased water absorption on the surface of ash particles [40].

Mortars with the highest portions of SSA showed the lowest density and the highest water absorption in comparison with others [13]. The same analysis concluded that the behavior of specimens with 10% SSA content instead of sand showed the best properties regarding density, absorption and capillarity, and consequently also regarding compressive strength. Generally, low compressive strengths were caused by high porosity.

Roughness and irregularity of SSA particles are the basic reason for increased absorption of water at the surface of the particles, and the accessible inner porosity is the reason for higher water absorption [40]. It was also noted that increased fineness of SSA particles resulted in reduced workability, which is logical due to the increased total surface area of the particles.

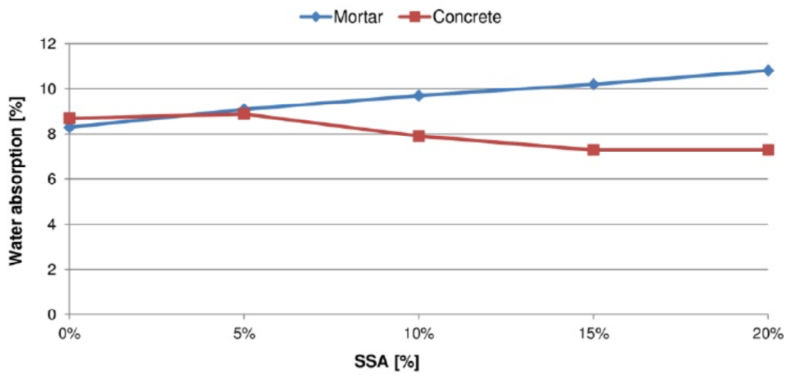

Fig. 8. Water absorption on mortar (cured for 90 d) and concrete (cured for 28 d) specimens, data from [13].

Donatello and Cheeseman [12] state that there are two clear trends: increasing SSA contents causes a decrease in compressive strength and milling of SSA generally improves strengths at a given percentage of SSA addition. Among the analyzed results, there are obvious differences in relative strengths, which can also be related to the process used to produce SSA.

In spite of lower strengths of mortars containing SSA, the strength activity indexes of SSA are higher than the minimum values required by the European standard for coal fly ash [20]. Minimum values of strength activity index (SAI – ratio of compressive strength between mortar with SSA and reference mortar) required by the EN 450 are 75% for hydration time of 7 and 28 days, and 85% for a hydration time of 90 days. Coutand et al. [20] published SAI values of 82% for a hydration time of 7 days and 92% for hydration times of 28 and 90 days. In other work [26], no differences were observed between control and experimental (with addition of 10% - 20% of SSA) precast concrete blocks with respect to dimensional stability.

3.1.5. Effect of SSA on leaching

Ongoing research has shown that about 78 - 98% Cd, Cr, Cu, Ni, Pb, and Zn present in sewage sludge are retained in the ash after incineration, whereas up to 98% of the Hg may be released into the atmosphere with the flue gas [51]. The potential environmental influence of SSA used in cementitious materials has been studied by several authors by analyzing leaching from concrete samples. Chen et al. [14] and Donatello et al. [52] concluded that it was within allowable limits according to all parameters according to the EN 15863 standard with periodic leachant renewal, unlike leaching from the ash at the landfill (Figs. 9 and 10), where excessive leaching of some heavy metals occurs, especially Mo, Sb, and Se. Ashes were tested by Chen et al. [14] according to the EN 12457 protocol (2002) by dispersing them into water at a liquid to solid ratio of 10 L/kg and mixing suspensions for 24 h at room temperature.

Cenni et al. [48] also analyzed leaching of Cd, Cu, Cr, Ni, Pb, and Zn from ash derived from coal

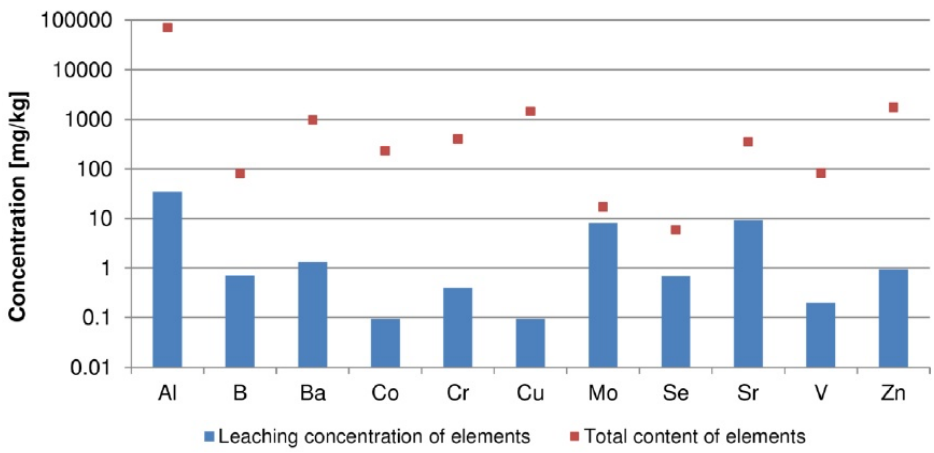

Fig. 9. Total content and leaching concentrations of selected elements after 24 h of agitation of the ash in water at room temperature, data from [14].

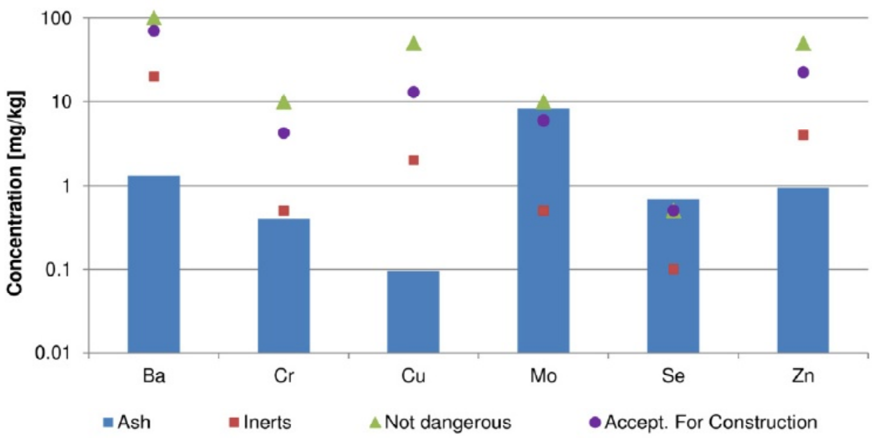

Fig. 10. Leaching concentrations of selected elements in the ashes [14] and the threshold values according to EU Landfill Directive 99/31/EC and French requirements for the tested material to be used for road construction.

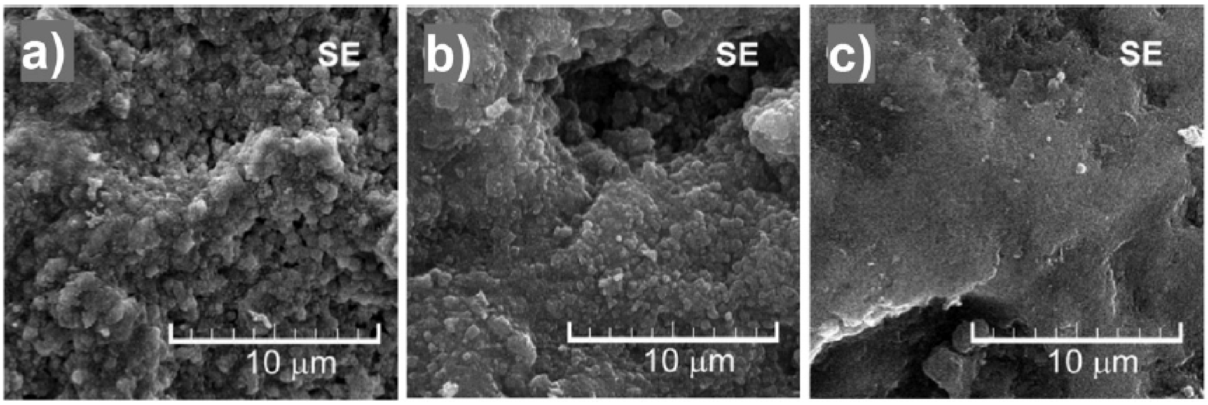

Fig. 11. SEM micrographs of hardened cement mortar with (a) 0%; (b) 10%; (c) 20% of SSA.

and sewage sludge co-firing and concluded that the concentration of these metals in the extracts was below the detection limit. According to Coutand et al. [20], the leaching behavior of mortars containing SSA is of the same order of magnitude as that of reference mortars without the SSA residue.

3.1.6. Effect of SSA on the microstructure of cementitious materials

A downward trend is observed in the density when the amount of SSA increases in cement mortars [13,26], which may be due to the low density of the residue and the large number of voids. According to Baeza-Brotons et al. [13], mixtures that contained the highest amount of SSA showed the lowest density and the greatest water absorption. Unlike cement mortars, concrete samples showed increasing density as the amount of SSA increased, while water absorption showed a tendency to decrease when the amount of SSA increased [13]. This behavior was probably due to the effect produced by the fine particles occupying the gaps between coarse aggregates, which compensated for its low relative density. General trend of porosity increase with increased SSA content was observed in cement mortar mixes [25]. Also, a decrease in porosity was observed when SSA obtained at higher incineration temperatures (ranging from 800 °C to 1000 °C) was used. Based on SEM analysis, conducted by the authors of this paper, on cement mortars which have incorporated the SSA with a content of up to 20%, characteristic grains of granulated materials that indicate the existence of chemically different phases, were observed even at lower microscope magnifications. At higher magnifications it is clear that the porosity of the material is higher for samples with higher SSA content (Fig. 11).

Crystal components (XRD analysis) and morphological (SEM analysis) specifics of cement mortar with the addition of SSA indicate that slight differences compared to the reference mixes were present which emphasizes the possible influence of SSA on differences in application in hardened mortars.

According to Kuo et al. [53] non-uniform and dense features of the structure are present in cement pastes containing 20% of SSA. However, many micro-pores, seen in the microstructure of hydrates of cement paste, are indicating that the interface between the SSA and C-S-H gel was bonded together well to produce a microstructure with fine and non-uniform particles.

The XRD analysis of cement pastes containing SSA hydrated for 28 days showed that the intensities of peaks were basically the same as that of Portland cement paste, but the diffraction peaks clearly decreased [21,54]. It was concluded that the hydration of the SSA cement pastes increased greatly because of the vast amount of $Ca(OH)_2$ and this enchanced the rate of strength development.

3.2. Use of SSA as substitute for aggregate

Another way of using SSA in cementitous materials is as a lightweight aggregate [55]. One of the basic characteristics of lightweight aggregates is porous texture and consequently considerable absorption of water. As SSA shows similar properties, it may be used directly as an admixture to concrete, in the form supplied by the producer, without any additional treatment. Kosior-Kazberuk [39] substituted a part of the 0-4 mm lightweight aggregate in concrete by SSA (because the particle size of the SSA used did not exceed 4 mm), with percentages of 0%, 10%, 25%, 50%, and 100% in relation to the total volume of aggregate. The ash density was 500 kg/m^3, and the specific gravity was 2520 kg/m^3, which brought it into the density category for lightweight aggregates (<1800 kg/m^3). It was shown that in mixtures with ash content substitution of 50% and 100%, workability was considerably reduced, and therefore it was necessary to increase the water content, owing to the looseness and coarse texture of SSA particles. Samples with up to 25% of aggregate replaced by SSA showed completely different behavior in relation to those with replacement percentages of 50% and 100%. It has been concluded that water absorption increases in parallel with the increased SSA content. Samples with substitution percentages of 50% and 100% showed the most significant decrease of compressive strength (from 60% to 75% of compressive strength of control samples). Samples cured for longer periods (90 and 180 days) with replacement percentages up to 25% showed compressive strengths even higher than those of control samples. The reason given was the development of pozzolanic properties and reactivity of SSA, because in this application the SSA was also acting partly as a binding agent. Samples with smaller replacement levels (up to 25%) showed better results, and the strengths arising from longer curing times (90 and 180 days) achieved the values obtained by control samples. The same study also analyzed the leaching of trace elements from samples, and the conclusion was that leaching was within permissible limits, and in many cases almost negligible. The author concluded that 25% was the acceptable replacement perecentage for substitution of lightweight aggregate by SSA in concretes used for structural purposes, while higher additions could be used in concretes for non-structural purposes.

Khanbilvardi and Afshari [56] concluded that concretes in which up to 30% of sand was substituted by SSA show reduced compressive strength after 28 days, by 22%. According to Jamshidi et al. [1], for concrete specimen hydration periods of 3 days, no significant differences were noticed between the control mix and the mixes with 5% and 10% replacement of sand by SSA. The mixture with 20% replacement showed a 20% decrease in the compressive strength, but an increase in the compressive strength with curing time was still observed. Flexural strength results showed that an increase in the SSA content leads to a decrease in flexural strength. According to Donatello and Cheeseman [12], increased water demand due to the more porous texture of SSA (compared to sand) limits the ratio of sand substitution by SSA to less than 5-10% of mass.

Basic characteristics, such as density, water absorption and compressive strength, of sintered pellets of sewage sludge ash are very similar or even superior to commercially available lightweight aggregates [57]. As the characteristics of SSA are similar to the characteristics of clay used for the production of lightweight aggregate, and in many parts of the world there is a shortage of available aggregate for production of cementitious materials, some research work has focused on the substitution of a part of the aggregate in concrete by SSA. Combination of SSA with a limited proportion of sewage sludge (<30% by weight) promotes formation of low density aggregate after sintering at temperatures of 1050-1150 °C, which is attributed to swelling caused by decomposition of organic matter present in sludge [58]. It has been concluded that sewage sludge or ash generated by its incineration may be used to produce ordinary or lightweight aggregate by sintering (separately or together). When joint use of sludge and ash is considered, the results indicate that the amount of sewage sludge should be less than 20%. In this application, for the production of lightweight aggregate, the important factors are the temperature of sintering, the proportion of each ingredient in the mix and the time of curing. When energy saving considerations are important, a mix consisting only of SSA is more suitable for production of aggregate with normal specific gravity. Mixes with sewage sludge content lower than 10% are good for obtaining low/medium dense aggregate, while the mixes with higher shares of sewage sludge (20-30%) are more suitable for sintering low density aggregates [58]. Triple mixes of SSA, clay and sewage sludge containing up to 64% SSA result in low density aggregates with characteristics similar to commercially available Lytag [59].

In addition to the applications reviewed above, there are possibilities of using SSA in mixes with return concrete. This is concrete remaining as surplus during concreting works that is returned to the batching plant. This can be crushed after curing and used as a material for load-bearing layers [60].

4. CONCLUSIONS

SSA consists of irregular particles, with high specific surface area, and this results in high water demand, decreased workability and inferior mechanical properties when used in mortar and concrete. However, additions of SSA up to 20% can be used without detrimental effects on the final product. Larger additions require process adjustments and this may affect concrete product performance. The results indicate that SSA can be used as a low-grade pozzolan or good-quality filler in concrete. Leaching from mortars and concrete is not affected by the presence of SSA. The environmental and economic benefits of using SSA in cementitious materials, include conservation of raw materials and production of "green products" and this has the potential to be significant depending on the end use and production scale. Recycling of SSA in cementitious materials is a practicable option that is a good alternative to landfilling. The use depends on regulations on the reuse of waste materials and on the readiness of the market to accept innovative products.

Sludge origin and the treatment technology influence the charactersitics of SSA and the final products containing SSA. The role of the process applied to generate SSA is also important and the furnace type, temperature, effect of various mixes during incineration control the properties of SSA. The precise effect of these factors on the physical and chemical properties of SSA, and also on the properties of resultant cementitious materials requires extensive research. Further technological and environmental tests are required, including field scale experiments prior to industrial application. Countries across the world and particularly developing countries that are experiencing rapid development of systems for the collection and treatment of wastewater, can benefit economically and environmentally from these applications. his section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

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