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Review

Recovery of Sewage Sludge in the Cement Industry

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Abstract: This paper presents an analysis of the literature that studies the possibility of sewage sludge being used in the cement industry to reduce carbon dioxide emissions from cement production and thus solve the problem of disposing of sewage sludge so that it is no longer stored, avoiding soil pollution with heavy metals, and reducing pressure on the environment. The ash of sewage sludge is a good pozzolanic material, because when it is finely ground, it can be used as a partial substitute for Portland cement. This reduces waste storage costs. Sewage sludge ash was mixed with cement, and it was analyzed to determine whether the paste obtained could be used as a raw material in the cement industry. The presented results are on the hydration characteristics of the sewage sludge ash, the compressive strength of the cement determined after different days, the workability of the cement, and the porosity of the cement paste and the ash.

Keywords: sewage sludge ash; circular economy; cement; waste

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1. Introduction

The fundamental principle of the economy was "resource-production-waste", in a linear direction, making a structural change necessary and vital. This change now exists as a concept and refers to the circular economy, in which waste must become a resource [1]. The sludge from the municipal water treatment process has characteristics that show that it can be used as a minor additive in the composition of cement. Given the situation regarding the poor management of sewage sludge, a good treatment of it could create an expansion for its correct recovery by using it in the cement industry [2]. This would reduce carbon dioxide emissions and solve the management of sewage sludge [3].

The development of urbanization implies an increased demand for cement, and implicitly, an increase in carbon dioxide emissions [4–6]. This paper highlights the positive impact of ash from sewage sludge in the construction industry. According to the CEMBUREAU Activity report 2020 ("Cementing the European GreenDeal"), the cement production in EU28 from 2019 was approx. 182 million tons [7]. If it contained a 1.5% minor addition of sewage sludge, it would have avoided the storage of this waste (made by EU28, in 2019), and would have led to avoiding emissions of about 1.8 million tons of CO_2 [7].

In the process of industrialization, pollution generating activities surpassed the self-cleaning and self-regulation capacity of the environment. It has become a high priority worldwide to produce environmentally friendly low carbon imprint products, including building materials [8–11].

An important and topical issue is environmental pollution. Thus, as the amount of industrial sludge residue increases, the management of excess sludge becomes problematic, and thus endangers the environment. It creates problems such as: (i) water pollution (underground by infiltration, and surface by runoff); (ii) air pollution (aerobic fermentation by gas release); and (iii) soil pollution (infestation by uncontrolled storage) [3,9,12,13].

From the cement industry about 900 kg of CO_2 are emitted, for every ton of cement produced, and anthropogenic CO_2 emissions worldwide are about 5% [10,11,14]. The manufacturing of one cubic meter of concrete (~2400 kg) is responsible for the emission of ~540 kg of CO_2 into the atmosphere [3,12].

There are seven cement factories in Romania, all with rotary clinker kilns and a dry process for cement production. If each cement plant in Romania would use 10,000 tons of dry sewage sludge as alternative fuel, for one year, approximately 25,000 tons of coal would be substituted and 60,000 tons of CO_2 emissions would be saved [15,16]. The amount of waste must be reduced by 50% before 2050; this category also includes sludge from wastewater treatment plants [5,13].

During periods of economic development, the increase in demand for cement is mainly due to infrastructure, construction, and industry projects. Globally, between 2000 and 2018, cement production increased, with an average annual growth rate of 6.2%, reaching 4200 million tons in 2018, compared to 1600 million tons produced in 2000, as seen in Figure 1 [7].

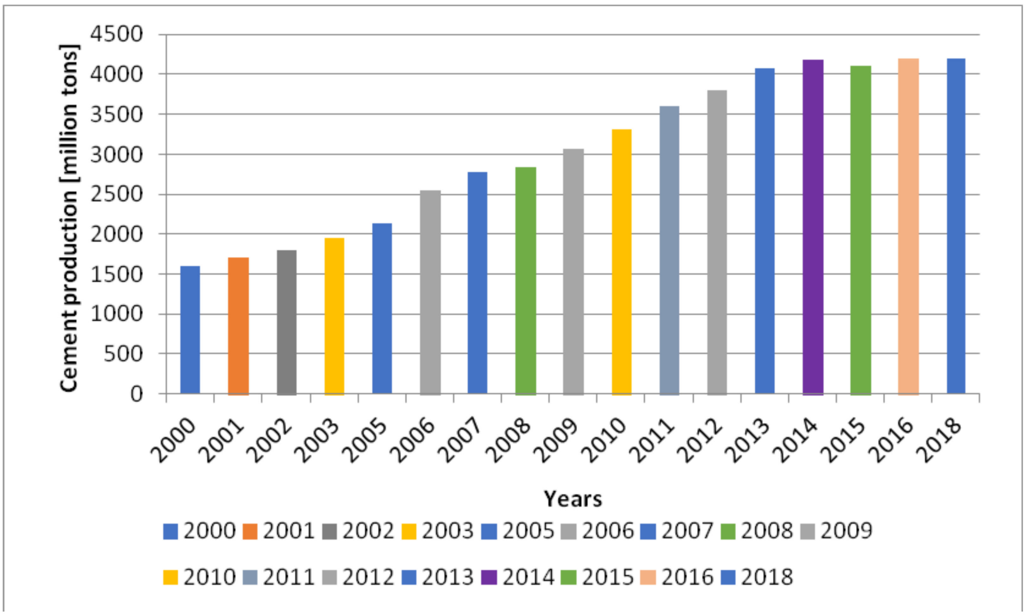


Figure 1. Global cement production in the years 2000–2018 [7].

According to Figure 2, the quantities of sludge generated by wastewater treatment plants in Romania during 2005–2018 are increasing (from 134 tons of dry matter/year recorded in 2005, to 520 tons of dry matter/year in 2018).

In this paper, sewage sludge ash as raw material for the cement industry has been analyzed [8,17–19]. The ash of sewage sludge comes from the incineration of sewage sludge from wastewater treatment plants, and has a high porosity, and irregular sand-like shape. It is a reactive material, which increases the strength of the mortar due to these pozzolanic properties [17,20]. The sewage sludge is dehydrated in the incineration plant up to 30% before burning in a fluidized bed oven at 800–900 °C.

Through the incineration process, the amount of waste is reduced; the ash can replace the cement [21].

By incineration, the volume of sewage sludge is reduced, this being a method of managing sewage sludge [22]. After incineration at a high temperature, the components of SiO_2, CaO, Al_2O_3 sludge are similar to those of cement [23]. Therefore, the use of sewage sludge ash in the cement industry reduces environmental pollution; reduces the amount of cement required; and has an economic, ecological, and energy saving impact [24–26]. When the ash of the sewage sludge is used as an additive to the cement, the pozzolanic activity is lower than that of the cement, determining a lower resistance and a high addition of water, which can be avoided by grinding the ash [27].

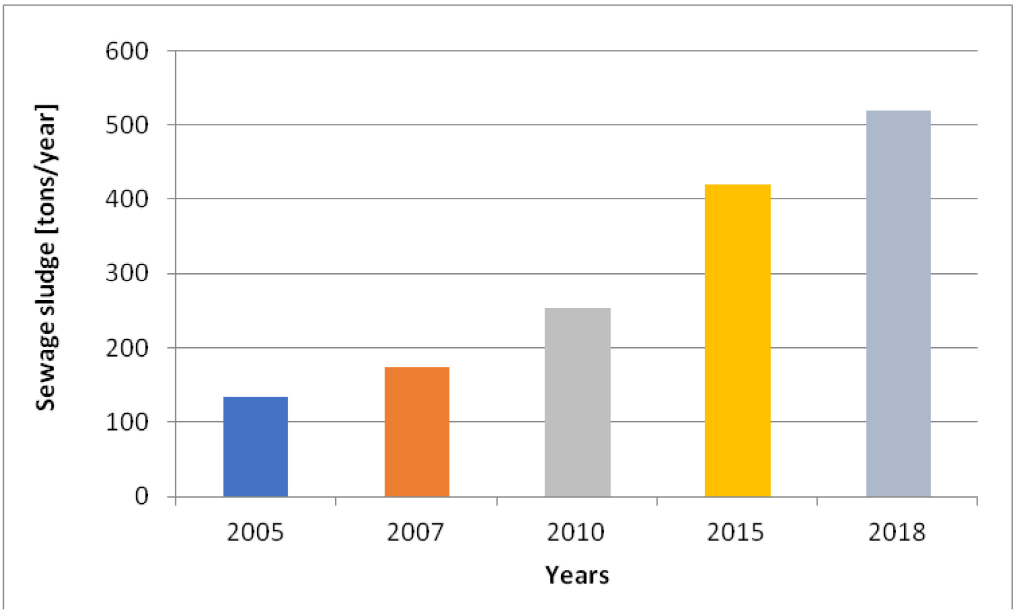


Figure 2. The amount of sludge generated in Romania [14].

2. Chemical Properties of Sewage Sludge Ash

2.1. Chemical Composition

It can be seen from Table 1, where the composition of the sewage sludge from a municipal waste treatment plant in Romania is presented, that it contains heavy metals such as cadmium; copper; lead; mercury; and chromium [3].

Table 1. Sewage sludge composition from a municipal waste treatment installation in Romania.

Indicatory	Unit Measure	Value
Net calorific value	GJ/t	8.92
Humidity	%	12.20
Mercury	mg/kg	0.809
Cadmium	mg/kg	2.17
Plumb	mg/kg	42.50
Crom	mg/kg	73.00
Cupru	mg/kg	370.00
Mangan	mg/kg	460.00
Arsen	mg/kg	6.14
Zinc	mg/kg	985.00
Petroleum products	mg/kg	7780.00

In Table 2, the oxide contents of dry sludge and Portland cement are shown.

Table 2. Oxide content [27–31].

The Component Element	Sewage Sludge Ash [%]					Portland Cement [%]				
	[29]	[30]	[27]	[28]	[31]	[29]	[30]	[27]	[28]	[31]
SiO_2	16.60	17.10	28.60	28.30	37.04	19.50	20.10	19.50	19.80	20.33
Al_2O_3	5.10	5.10	17.60	12.50	15.24	6.00	4.91	4.40	3.90	5.21
Fe_2O_3	9.10	15.70	4.40	18.60	14.03	3.10	5.43	2.60	3.20	3.13
MnO	-	0.09	-	0.20	-	-	0.04	-	0.10	-
P_2O_5	15.00	20.20	1.90	0.50	9.12	-	0.23	-	0.90	0.20
CaO	12.90	23.80	20.10	10.60	6.91	62.10	65.70	60.50	65.20	64.00
K_2O	2.80	1.57	1.90	1.90	2.77	-	0.81	0.90	0.70	0.63
MgO	3.80	2.32	2.30	3.20	2.80	1.70	0.53	2.90	1.50	1.62
SO_3	2.10	2.02	2.00	6.20	3.66	2.60	4.74	3.63	5.50	4.17
Na_2O	3.50	1.15	1.23	7.40	7.11	0.80	0.67	0.24	-	-
TiO_2	-	0.83	1.50	0.50	0.38	-	0.35	0.20	0.30	0.27
ZnO	-	-	0.52	-	-	-	-	-	-	-
Cl	0.01	0.01	-	-	-	0.03	0.10	-	-	-
Loss on ignition (LOI)	-	-	0.70	-	-	-	-	2.70	-	-

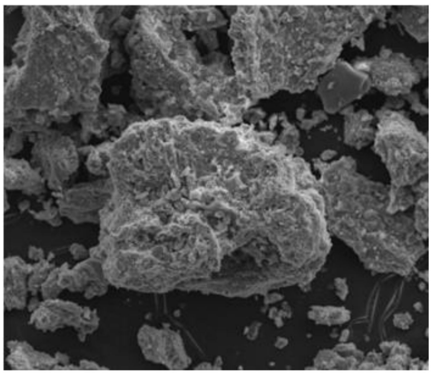
According to Table 2, it can be observed that the common elements in Portland cement and ash from sewage sludge are: Ca, Si, Al, and Fe.

It is observed that SiO_2, Fe_2O_3, and Al_2O_3 are predominate in the composition of the incinerated sewage sludge; these being oxides involved in the pozzolanic reaction [20,23,28]. A high content of P_2O_5 in the ash can have a negative impact on the hardening of the paste when used as a cement additive, longer setting times and slow development of strength [16,32].

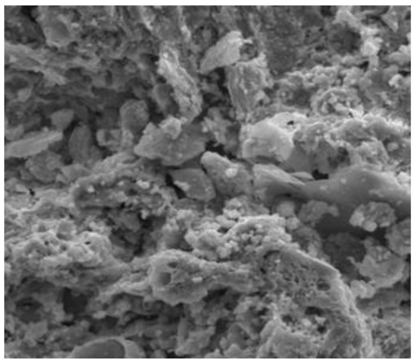
The contents of MnO, K_2O, MgO, and SO_3 from the sewage sludge ash are similar to Portland cement. Other oxides contained are: CaO, SO_3, K_2O, MgO, and P_2O_5 [31].

The SO_3 contents of Portland cement and sewage sludge ash are less than 4%, and comply with the provisions of the European Standard, SR EN 197-1 [33].

In Figure 3a,b, scanning electron microscopy SEM images of ash sewage sludge are presented; this is a granular material with an irregular shape and high porosity.



(**a**)



(**b**)

Figure 3. Images of sewage sludge ash (**a**) magnification 1000× (**b**) magnification 4000× by scanning electron microscopy (SEM) [25].

The use of ash as a raw material aims to reduce the cement content, reduce costs, obtain a low hydration temperature, obtain higher strengths of concrete at older ages of hardening of the paste, and improve durability [34,35].

In Table 3, the properties of Portland cement CEM I are presented according to the European Standard, SR EN 197-1.

Table 3. CEM I characteristics [33].

Type of Cement CEM I	Characteristics	Conditions
CEM I 42.5 R	Initial setting time	≥60 min
	Compressive strength 2 days	≥20 MPa
	Compressive strength 28 days	≥42.5 MPa . . . ≤62.5 MPa
	Loss on ignition	≤5%
	Sulfate content (as SO_3)	≤4%
	Chloride content	≤0.10%
CEM I 52.5 R	Initial setting time	≥100 min ≤ 140 min
	Compressive strength 2 days	≥30 MPa
	Compressive strength 28 days	≥52.5 MPa
	Loss on ignition	≤5%
	Sulfate content (as SO_3)	≤4%
	Chloride content	≤0.10%

The European Standard, SR EN 197-1, defines five classes of common cement that comprise Portland cement as a main constituent, and these are presented in Table 4.

Table 4. Types of cement [33].

Class	Description	Constituents
CEM I	Portland cement	Comprising Portland cement and up to 5% of minor additional constituents
CEM II	Portland-composite cement	Portland cement and up to 35% of other single constituents
CEM III	Blast furnace cement	Portland cement and higher percentages of blast furnace slag.
CEM IV	Pozzolanic cement	Portland cement and up to 55% of pozzolanic constituents.
CEM V	Composite cement	Portland cement, blast furnace slag, or fly ash and pozzolana.

In this paper, we analyze pastes containing 5%, 10%, 15%, and 20% sewage sludge ash.

2.2. Hydration Characteristics of Ash

Hydration of the material with sewage sludge ash increases; their resistance is developed by using a large amount of $Ca(OH)_2$ [22].

As the ash content increases, the capillary network of cement has changed, and the coefficient of water absorption by capillarity has doubled [24,35,36].

Paste with cement and ash has a shorter preparation time than Portland cement paste because the hydration rate of aluminum oxide in the ash of sewage sludge is higher than that of silicate in cement [21,22]. At a content of 10%, Portland cement-ash sewage sludge at 72 h, has the heat of hydration of 672.94 [J/g]; at a content of 20%, Portland cement-ash sewage sludge at 72 h has the heat of hydration of 505.90 [J/g]; at a content of 30%, Portland cement-ash of sewage sludge at 72 h has the cumulative heat of 443.13 [J/g]. The heat of hydration of the Portland cement sewage sludge ash paste decreases with the increase of the ash content of the Portland cement sewage sludge [23]. Porous particles of sewage sludge ash absorb more water, increasing the heat release rate of Portland cement.

By adding 5% ash to the cement, a low absorption capacity, a longer material life, and a high durability are obtained [5].

3. Mechanical Properties of Sewage Sludge Ash

3.1. Compression Strength

To see the strength of the cement, a compressive strength test was performed.

The compressive strength of the cement determined after 1, 7, 28, and 90 days for different pastes with sewage sludge ash added at concentrations of 5%, 10%, 15%, and 20% compared to Portland cement (0%) is shown in Table 5. This shows that the ash of sewage sludge added in proportions of 5% and 10% at 28 days had values similar to the compressive strength of Portland cement [28,31,37].

The compressive strength decreased proportionally with an increase in the concentration of added ash compared to cement strength, and increased the curing time of cement [6,24,32,36]. The compressive strength of the paste with cement and the addition of ash of 5% and 10% had values similar to the compressive strength of cement [28].

The compressive strength of cement paste and ash increased with the increasing binder aging due to cement hydration [38,39].

Sewage sludge ash has a lower pozzolanic reactivity; its porous nature determines the absorption of a larger amount of water from the mixtures, thus reducing the effect of diluting the cement [27].

Higher strength values were recorded when the ash had a small grain size compared to the coarse grain at the same ash content due to its higher reactivity; the increase in the strength of the material was also influenced by the hydroscopic nature of the ash, which absorbed more water [22,28,32,40].

In the material to which 5% and 10% ash were added, the compressive strength had higher values, with the increase of the hardening period [30,40].

Table 5. Compressive strength for different concentrations [6,27–30].

Sample		0%	5%	10%	15%	20%
	[27]	21.00	-	-	-	25.00
1 day, [N/mm^2]	[29]	10.00	-	9.00	-	8.00
	[30]	7.43	-	2.11	-	-
	[6]	7.95	7.39	6.85	6.07	5.84
7 day, [N/mm^2]	[27]	34.00	-	-	-	33.00
	[29]	20.00	-	19.00	-	18.00
	[30]	23.39	-	22.75	-	-
	[6]	23.21	21.22	19.62	17.03	14.73
	[28]	34.00	-	-	-	27.00
28 day, [N/mm^2]	[27]	45.00	-	-	-	43.00
	[30]	35.02	-	35.53	-	-
	[29]	48.00	-	42.00	-	40.00
	[6]	30.07	33.09	25.24	23.16	15.68
	[28]	42.00	-	-	-	38.00
90 day, [N/mm^2]	[28]	47.00	-	-	-	46.00
	[30]	42.06	-	44.30	-	-
	[29]	55.00	-	50.00	-	45.00
	[27]	49.00	-	-	-	47.00

3.2. Workability

In the case of the material to which 20% ash was added, the setting time increased; the 10% ash recipe had a setting time similar to that of cement [27,41]. By ensuring a water/cement ratio for the material with sewage sludge ash, a stable volume was obtained, and the workability was slightly reduced compared to Portland cement paste [37].

The setting time of the material increased with the increase of the gray granulation [20].

Table 6 shows the setting times for different concentrations of ash added to the cement.

Table 6. Portland cement setting time and sewage sludge paste [29,41].

Sample	Initial Time [29,41] [h:min]		Final Time [29,41] [h:min]		Water /Paste [36]	Volume Stability [Expansion, mm]
Cement Portland	1:50	3:30	3:10	4:16	0.34	0
10 % SSA	2:0	3:30	4:45	4:58	0.38	0
20 % SSA	2:45	2:80	6:00	6:00	-	0

SSA: sewage sludge ash.

3.3. The Porosity

The porosity of the cement paste and ash influenced the physical properties if this porous paste was hydrated; it was compact and can be used as a substitute for cement [41,42].The porosity was higher for the material to which a larger amount of ash had been added (Figure 4 and Table 7) [41,42].

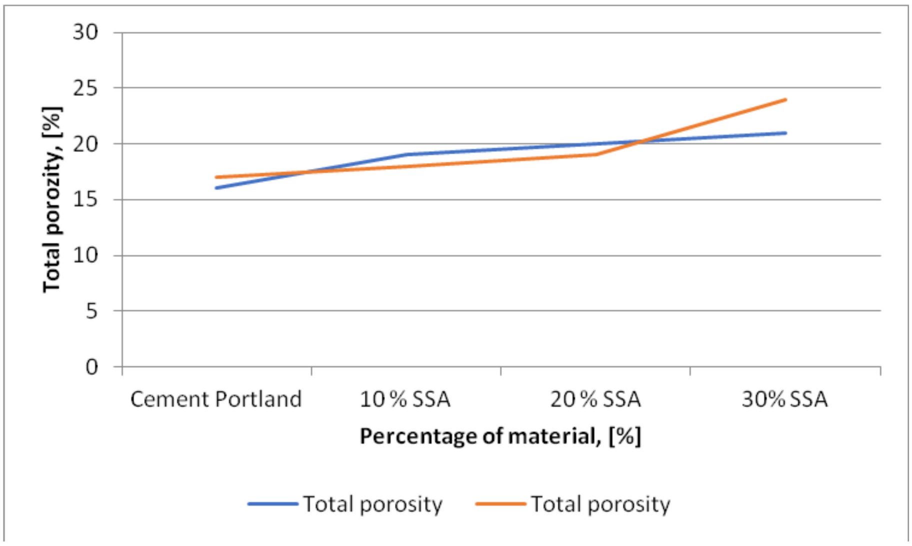


Figure 4. Total porosity [41,42].

Table 7. Total porosity.

Sample	Total Porosity [%] [41,42]	
Cement Portland	16	17
10 % SSA	19	18
20 % SSA	20	19
30% SSA	21	24

4. Conclusions

The sewage sludge ash analyzed in this paper meets the standard conditions to be used as an additive in the cement industry: the content of SO_3 of ash is less than or equal to 4%, the compressive strength at 28 days is greater than or equal to 42.5 MPa, and the initial setting time is greater than or equal to 60 min [15,17].

Using sewage sludge ash as a cement substitute reduces the pollutants resulting from the manufacturing of cement and reduces the storage space of the cement [6]. Its use in the cement industry aims to reduce the cement content, reduce costs, obtain a low hydration temperature, improve workability, and obtain higher strengths of concrete at higher curing ages (higher number of days). The oxides contained in sewage sludge ash are similar to those in Portland cement, so the ash can be used as an additive in the manufacturing of cement [6]. Sewage sludge ash has a porous, irregular structure, and must be hydrated in order to be used as an additive in the cement industry [39,42].

The compressive strength of cement paste was similar to that of cement for adding a small amount of ash (5% and 10%) [28].

The setting time of the material increased with the increase of the gray granulation [20].

Given the commitments of major cement producers to become CO_2-neutral by 2050, the inclusion of this waste in cement outlines a perspective that can contribute to meeting the targets set [43].

The use of ash as an additive in the cement industry is a good choice to reduce the pressure on the environment, but it has to be considered that when the ash of the sewage sludge is used as an additive to the cement, the pozzolanic activity is lower than that of the cement. This causes a lower resistance and a high addition of water, which can be avoided by grinding the ash [44,45].

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References

1. Rusanescu, C.O.; Rusanescu, M.; Jinescu, C.; Durbaca, I. Recovery of Treated Sludge. *Rev. Chim.* **2019**, *70*, 3477–3481. [CrossRef]
2. Christodoulou, A.; Stamatelatou, K. Overview of legislation on sewage sludge management in developed countries worldwide. *Water Sci. Technol.* **2016**, *73*, 453–462. [CrossRef] [PubMed]
3. Purdea, L.; Rusanescu, C.O.; Tucureanu, M.C. Alternative for the Use of Sewage Sludge in Romania. *Rev. Chim.* **2019**, *70*, 1967–1970. [CrossRef]
4. Voicu, G.; Ciobanu, C.; Istrate, I.A.; Tudor, P. Emissions Control of Hydrochloric and Fluorhydric Acid in cement Factories from Romania. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1019. [CrossRef] [PubMed]
5. Andrew, R. Global CO_2 emissions from cement production 2018. *Earth Syst. Sci. Data ESSD* **2018**, *10*, 195–217. [CrossRef]
6. Ing, D.S.; Chin, S.C.; Guan, T.K.; Suil, A. The use of sewage sludge ash (SSA) as partial replacement of cement in concrete. *ARPN J. Eng. Appl. Sci.* **2016**, *11*, 3771–3775.
7. Activity Report CEMBUREAU. 2020. Available online: https://www.cembureau.eu/media/m2ugw54y/cembureau-2020-activity-report.pdf (accessed on 2 September 2021).
8. Chen, Z.; Poon, C.S. Comparative studies on the effects of sewage sludge ash and fly ash on cement hydration and properties of cement mortars. *Constr. Build. Mater.* **2017**, *154*, 791–803. [CrossRef]
9. Țucureanu, M.C.; Rusănescu, C.O.; Purdea, L. Polluting Emissions from Incineration and Waste Installations. *Rev. Chim.* **2019**, *70*, 2385–2387. [CrossRef]
10. Eurostat. Eurostat Database: Sewage Sludge Production and Disposal from Urban Wastewater. 2021. Available online: http://appsso.eurostat.ec.europa.eu/nui/show.do?lang=en&dataset=env_ww_spd (accessed on 2 September 2021).
11. Yang, G.; Zhang, G.M.; Wang, H.C. Current state of sludge production, management, treatment and disposal in China. *Water Res.* **2015**, *78*, 60–73. [CrossRef]
12. Zhang, T.; Gao, P.; Gao, P.; Wei, J.; Yu, Q. Effectiveness of novel and traditional methods to incorporate industrial wastes in cementitious materials—An overview. *Resour. Conserv. Recycl.* **2013**, *74*, 134–143. [CrossRef]

13. Ulmanu, M.; Matsi, T.; Gament, E.; Olănescu, G.; Predescu, C.; Sohaciu, M. The remedial treatment of soil polluted with heavy metals using fly ash. *UPB Sci. Bull. B Chem. Mater. Sci.* **2007**, *69*, 109–116.
14. Tepeș-Bobescu, L. Aspects regarding the environmental impact due to the use of alternative fuels in cement manufacturing process. *Int. J. Eng.* **2018**, *4*, 75–78.
15. Ghiocel, A.N.; Panaitescu, V.N. Using sewage sludge as an alternative fuel for the cement production process. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *400*, 022029. [CrossRef]
16. Haustein, E.; Kuryłowicz-Cudowska, A.; Łuczkiewicz, A.; Fudala-Ksiazek, S.; Cieślik, B.M. Influence of Cement Replacement with Sewage Sludge Ash (SSA) on the Heat of Hydration of Cement Mortar. *Materials* **2022**, *15*, 1547. [CrossRef]
17. Amminudin, A.L.; Ramadhansyah, P.J.; Doh, S.I.; Mangi, S.A.; Haziman, W.I.M. Effect of Dried Sewage Sludge on Compressive Strength of Concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *712*, 012042. [CrossRef]
18. Monzó, J.; Payá, J.; Borrachero, M.; Girbés, I. Reuse of sewage sludge ashes (SSA) in cement mixtures: The effect of SSA on the workability of cement mortars. *J. Waste Manag.* **2003**, *23*, 373–381. [CrossRef]
19. Pan, J.R.; Huang, C.; Lin, S. Reuse of fresh water sludge in cement making. *Water Sci. Technol.* **2004**, *50*, 183–188. [CrossRef] [PubMed]
20. Yusuf, R.O.; Noor, Z.Z.; Din, M.F.M.; Abba, A.H. Use of sewage sludge ash (SSA) in the production of cement and concrete—A review. *Int. J. Glob. Environ. Issues* **2012**, *12*, 214. [CrossRef]
21. Lin, D.-F.; Luo, H.-L.; Sheen, Y.-N. Glazed Tiles Manufactured from Incinerated Sewage Sludge Ash and Clay. *J. Air Waste Manag. Assoc.* **2005**, *55*, 163–172. [CrossRef]
22. Donatello, S.; Cheeseman, C.R. Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *J. Waste Manag.* **2013**, *33*, 2328–2340. [CrossRef] [PubMed]
23. Malhotra, V.M.; Ramezanianpour, A.A. *Fly Ash in Concrete*; Canada Center for Mineral and Energy (CANMET): Ottawa, ON, Canada, 1994.
24. Jamshidi, A.; Jamshidi, M.; Mehrdadi, N.; Shasavandi, A.; Pacheco-Torgal, F. Mechanical Performance of Concrete with Partial Replacement of Sand by Sewage Sludge Ash from Incineration. *Mater. Sci. Forum* **2012**, *730–732*, 462–467. [CrossRef]
25. Rutkowska, G.; Wichowski, P.; Franus, M.; Mendryk, M.; Fronczyk, J. Modification of Ordinary Concrete Using Fly Ash from Combustion of Municipal Sewage Sludge. *Materials* **2020**, *13*, 487. [CrossRef] [PubMed]
26. David, T.K.; Nair, S.K. Compressive Strength of Concrete with Sewage Sludge Ash (SSA). *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *371*, 012009. [CrossRef]
27. Mejdia, M.; Saillioa, M.; Chaussadenta, T.; Diveta, L.; Tagnit-Hamou, A. Hydration mechanisms of sewage sludge ashes used as cement replacement. *Cem. Concr. Res.* **2020**, *135*, 106–115. [CrossRef]
28. Chen, Z.; Poon, C.S. Comparing the use of sewage sludge ash and glass powder in cement mortars. *Environ. Technol.* **2017**, *38*, 1390–1398. [CrossRef] [PubMed]
29. Piasta, W.; Lukawska, M. The Effect of Sewage Sludge Ash on Properties of Cement Composites. *Procedia Eng.* **2016**, *161*, 1018–1024. [CrossRef]
30. Kappel, A.; Ottosen, L.M.; Kirkelund, G.M. Colour, compressive strength and workability of mortars with an iron rich sewage sludge ash. *Constr. Build. Mater.* **2017**, *157*, 1199–1205. [CrossRef]
31. Zhou, Y.; Li, J.; Lu, J.; Cheeseman, C.; Poon, C.S. Recycling incinerated sewage sludge ash (ISSA) as a cementi-tious binder by lime activation. *J. Clean. Prod.* **2020**, *244*, 118856. [CrossRef]
32. Krejcirikova, B.; Ottosen, L.M.; Kirkelund, G.M.; Rode, C.; Peuhkuri, R. Characterization of sewage sludge ash and its effect on moisture physics of mortar. *J. Build. Eng.* **2019**, *21*, 396–403. [CrossRef]
33. *EN 197-1; Cement—Part 1: Composition, Specifications and Conformity Criteria for Common Cements*; European Committee for Standardization: Brussels, Belgium, 2011.
34. Fontes, C.M.A.; Toledo Filho, R.D.; Barbosa, M.C. Sewage sludge ash (SSA) in high performance concrete: Characterization and application. *Rev. Ibracon Estrut. Mater.* **2016**, *9*, 989–1006. [CrossRef]
35. Wang, K.-S.; Chiou, I.-J.; Chen, C.-H.; Wang, D. Lightweight properties and pore structure of foamed material made from sewage sludge ash. *Constr. Build. Mater.* **2005**, *19*, 627–633. [CrossRef]
36. Rutkowska, G.; Wichowski, P.; Fronczyk, J.; Franus, M.; Chalecki, M. Use of fly ashes from municipal sewage sludge combustion in production of ash concretes. *Constr. Build. Mater.* **2018**, *188*, 874–883. [CrossRef]
37. Baeza, F.; Payá, J.; Galao, O.; Saval, J.M.; Garcés, P. Blending of Industrial Waste from Different Sources as Partial Substitution of Portland cement in Pastes and Mortars. *J. Constr. Build. Mater.* **2014**, *66*, 645–653. [CrossRef]
38. Weeks, C.; Hand, R.J.; Sharp, J.H. Retardation of cement hydration caused by heavy metals present in ISF slag used as aggregate. *Cem. Concr. Compos.* **2008**, *30*, 970–978. [CrossRef]
39. Cyr, M.; Coutand, M.; Clastres, P. Technological and environmental behavior of sewage sludge ash (SSA) in cement-based materials. *Cem. Concr. Res.* **2007**, *37*, 1278–1289. [CrossRef]
40. Liu, M.; Zhao, Y.; Xiao, Y.; Yu, Z. Performance of cement pastes containing sewage sludge ash at elevated temperatures. *Constr. Build. Mater.* **2019**, *211*, 785–795. [CrossRef]
41. Garcés, P.; Pérez Carrión, M.; García-Alcocel, E.; Payá, J.; Monzó, J.; Borrachero, M.V. Mechanical and physical properties of cement blended with sewage sludge ash. *Waste Manag.* **2008**, *28*, 2495–2502. [CrossRef]

42. Vouk, D.; Nakic, D.; Stirmer, N.; Cheeseman, C.R. Use of sewage sludge ash in cementitious materials. *Rev. Adv. Mater. Sci.* **2017**, *49*, 158–170.
43. Akashi, O.; Hanaoka, T. Technological feasibility and costs of achieving a 50% reduction of global GHG emissions by 2050: Mid- and long-term perspectives. *Sustain. Sci.* **2012**, *7*, 139–156. [CrossRef]
44. Donatello, S.; Freeman-Pask, A.; Tyrer, M.; Cheeseman, C. Effect of milling and acid washing on the pozzolanic activity of incinerator sewage sludge ash. *Cem. Concr. Compos.* **2010**, *32*, 54–61. [CrossRef]
45. Hasanbeigi, A.; Lu, H.; Williams, C.; Price, L. *International Best Practices for Pre-Processing and Co-Processing Municipal Solid Waste and Sewage Sludge in the Cement Industry*; Ernest Orlando Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2012.