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Title: Sewage Sludge Ash Characteristics and Potential for Use in Concrete

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Abstract

Sewage Sludge Ash (SSA) use in concrete related applications is assessed through systematic review involving analysis and evaluation of the global literature found published since 1983. The material characteristics indicate potential for various applications: in small dosages as raw feed in Portland cement production, as fine and filler aggregates, or in ground form as cement component, with manageable effects on performance. Using manufactured SSA aggregate, concrete strength suitable for structural applications and lightweight properties comparable to Leca are attainable. SSA can be used in bulk, in controlled low strength materials (CLSM), aerated and foamed concretes. Reported case studies give encouraging signals.

Key Words: Sewage sludge ash, Systematic review, Concrete

Highlights:

- Globally published literature on SSA use in concrete analysed and evaluated.
- SSA use as raw feed for cement and in ground form as cement component.
- SSA use as fine and filler aggregates and in lightweight manufactured aggregates.
- Use in bulk quantities in CLSM, aerated and foamed concrete.
- Suggestions for developing SSA as value-added sustainable construction material.

1. Introduction

Sustainable waste management has been incorporated as a core principle in European (EU Directive 2008/98/EC on waste) and worldwide (United Nations Framework Convention on climate change, 1992) legislation. A more environmental friendly hierarchy of waste treatment options, of which recycling and incineration rank above disposal, is now prescribed by law.

Sewage sludge is a by-product of waste water treatment. Past disposal methods of this waste are no longer readily acceptable, for example, in Europe, disposal at sea has been banned since 1998 (EU Urban Waste Water Directive 91/271/EC), spreading on farmland has been restricted due to cautious approaches adopted by countries for health reasons and mandatory targets have been set to reduce the biodegradable waste landfilled fractions (EU Landfill Directive 1999/31/EC).

The incineration process reduces the waste by approximately 70% by mass and 90% by volume, leaving behind residual sewage sludge ash (SSA) and has become one of the most appropriate management options to deal with the volumes produced and the potentially unsafe elements the sewage sludge contains. Approximately 10 Mt dry mass of sewage sludge is produced per annum in the 28 European member states, of which, 22% is incinerated [1].

Though significantly less than municipal solid waste production, this quantity is still significant at a local level and indeed environmentally acceptable treatment of all waste streams, including SSA, is needed and, where appropriate, their sustainable use as secondary materials. Indeed, the construction industry is increasingly expected to play a major role in achieving the target of zero waste and as such, an evaluation of the use of SSA in concrete can be useful and timely.

2. The Project

This paper examines the use of SSA in concrete and concrete related applications. A systematic review of globally published literature in the English medium is undertaken, involving analysis, evaluation and synthesis of data therein, covering the material's physical and chemical characteristics and its use as raw feed for cement clinker and as cement components in producing cement paste, mortar and concrete mixtures, as well as fine, filler and manufactured lightweight aggregates.

The compendium of the data is based on a total of 156 publications, dating from 1983 - 2015 and originating in 30 countries across Europe (72 publications), Asia (65), North America (11), South America (4), Africa (3) and Australia (1), with the largest contributions from Taiwan (27 publications), UK (19), Spain (17) and Japan (16).

3. SSA Characteristics

Density

The specific gravity of SSA has been found to range from 1.8 - 2.9, though the bulk of results were skewed towards the upper end of this band with a mean value of 2.5 and standard deviation of 0.3 [2-26]. The material is somewhat comparable to light sand and less dense than Portland cement (3.15). It has been shown that density increases with the incineration temperature, though the rate of increase drops off above 1000°C. The low ratio of bulk density (average 805 kg/m^3) [2, 8, 9, 17, 22, 23 and 26-28] to particle density is also indicative of the porous nature of SSA.

Fineness and Grading

For as-produced SSA, the data presented in the published literature suggests that the material predominantly falls in the silt (2.5 - 62.5µm) and fine sand (62.5 – 250µm) size fractions, with mean diameters ranging from 50 – 260 µm [4, 5, 8, 9, 13, 14, 29, 30 and 31].

A selection of as-produced material grading curves is shown in Figure 1a. Though variable, for the most part the material is consistent within the above mean diameter range, indicating suitability for use as filler or fine aggregates in concrete, possibly with minor modifications.

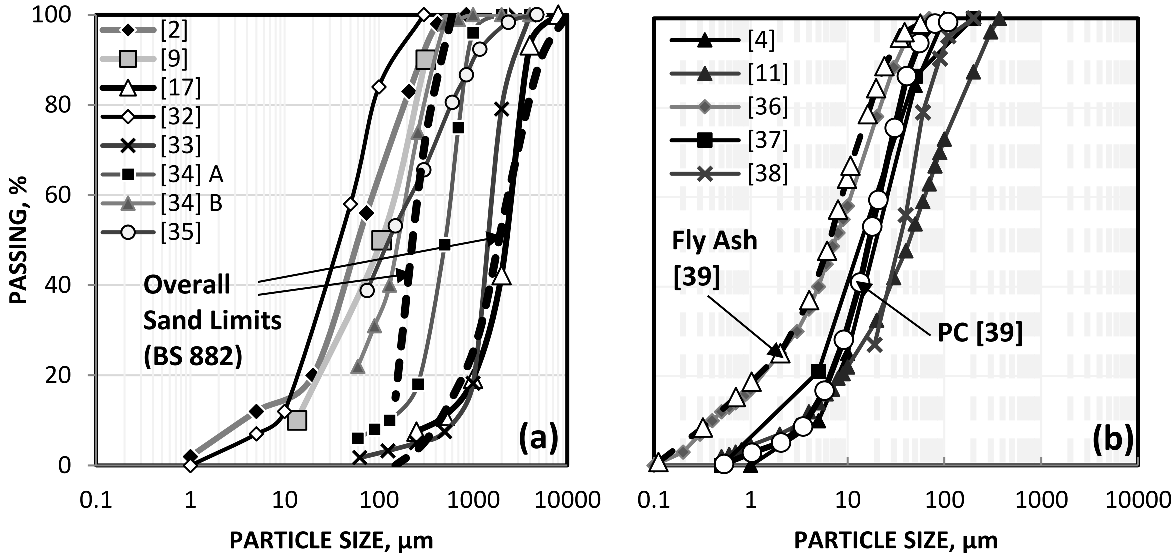


Figure 1: Particle size distributions of (a) as-produced SSA with overall sand limits in concrete (BS 882) and (b) ground SSA with PC and fly ash samples.

SSA ground for use as a cementitious component (Figure 1b) can achieve well graded size distributions similar to Portland cement clinker (PC) and fly ash (class F). BET specific surface area and Blaine fineness however varied over a wide range from 2500 - 23100 m^2/kg [4, 9, 11, 21, 24, 25, 36 and 38] and 500 - 3900 m^2/kg [4, 12, 21, 24, 31 and 40] respectively. The marked variability and discrepancies compared to typical Portland cement (e.g. BET 350 - 380 m^2/kg [41]), suggest that these fineness measures are not ideally suited to assess SSA as a potential cementitious material, due to the effect of its irregular particle shapes and porous microstructure.

Morphology

SSA consists of irregular particles with rough surface textures and a porous microstructure [3, 4, 7, 12, 13, 16, 17, 25, 31, 37, 38 and 42-46] which may lead to high absorption and an increase in the water demand of concrete using SSA. Indeed, water absorption values ranging from 8 - 20% have been reported [10, 13, 47 and 48], which is substantially higher than natural sand, which is typically 1 - 3%. Superplasticizers are one option to consider as an admixture to counteract higher water demand resulting from the use of SSA in mortar and concrete.

Oxide Composition

The oxide composition of SSA has been widely reported [2, 7, 11, 13, 14, 16-18, 20, 22-24, 28, 31, 32, 34, 36-38, 40, 44, 45, 49-102]. A breakdown of publications produced per year is presented in Figure 2, showing that the data has been published over a period of 26 years, though as a sign of growing interest in the use of sustainable materials, the majority of the research has been undertaken in the last 10 years.

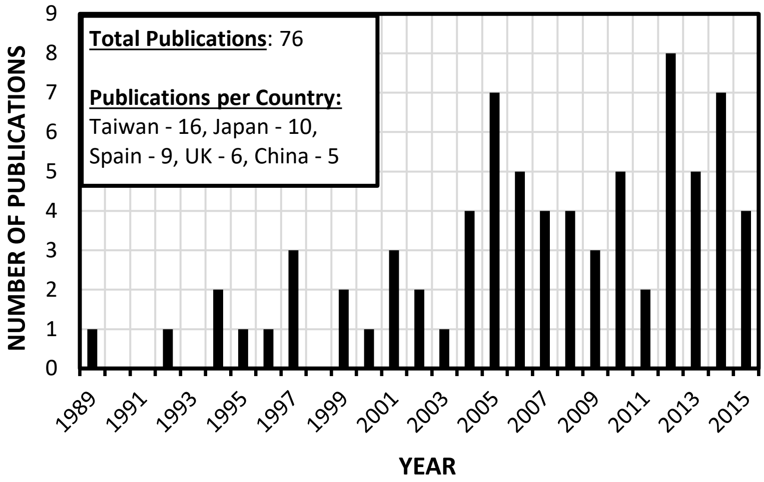
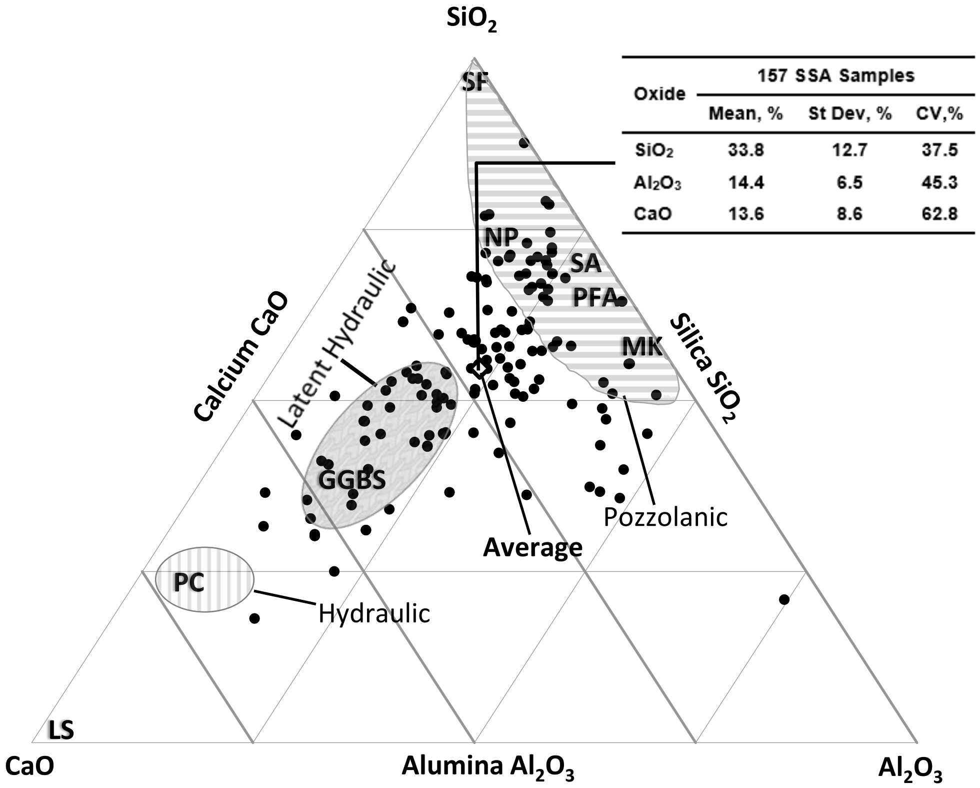


Figure 2: Rate of publication of the oxide composition data on SSA

The main oxides in SSA are reported as SiO_2, Al_2O_3 and CaO, while Fe_2O_3, Na_2O, MgO, P_2O_5, SO_3 and others are present in smaller quantities. A ternary diagram of the main oxide contents is plotted for 157 SSA samples taken from the above 76 publications, in Figure 3, along with typical contents for more established cementitious materials. The calculated mean, standard deviation (St Dev) and coefficient of variation (CV) values for SiO_2, Al_2O_3 and CaO are also given. This Figure shows that the majority of results fall around the latent hydraulic and pozzolanic regions, suggesting potential for SSA use as a cementitious component in concrete.

The mean aluminium content of approximately 14% calculated for SSA is much greater than the typical Portland cement content (approximately 5%), suggesting natural suitability for use in aerated concrete, which typically involves the use of foaming agents such as aluminium powder to react with



Oxide	157 SSA Samples		
	Mean, %	St Dev, %	CV,%
SiO$_2$	33.8	12.7	37.5
Al$_2$O$_3$	14.4	6.5	45.3
CaO	13.6	8.6	62.8

Figure 3: Ternary plot of SiO$_2$, Al$_2$O$_3$ and CaO contents for SSA

Note: PC = Portland cement, GGBS = ground granulated blastfurnace slag, PFA = pulverised fuel ash, MK = metakaolin, SA = shale ash, NP = natural pozzolan, SF = silica fume and LS = limestone.

cement to bring about expansion and the formation of a lightweight material. The high aluminium content of SSA may also benefit concrete resistance to chloride attack, due to the chloride binding capacity of amorphous alumina.

Loss on Ignition (LOI)

The LOI data for SSA obtained from the sourced literature yielded an average value of 3.5%, though occasionally very high values up to 13% have been reported [2, 7, 12, 13, 15-17, 30, 31, 52, 64, 80, 81, 92, 94, 96, 103 and 104]. Thus, it is possible for SSA, as presently produced, to be generally able to comply with the LOI limit of 5% set for cement in EN 197 (2011) and fly ash for concrete in EN 450

(2012). Where SSA is earmarked for specific use in concrete, a thorough burn during incineration should be able to control the LOI.

Mineralogy

Quartz and hematite have been identified as the most abundant minerals in SSA, while many other iron oxides, iron phosphates, calcium phosphates and aluminium phosphates have been reported to a lesser degree [3-5, 11-13, 16, 21, 24, 29-32, 43-45, 51, 58, 59, 64, 68, 74, 76, 77, 79, 94, 95, 99, 102 and 105-110]. The amorphous content of SSA ranged from 35 - 75%, which suggests that the material is somewhat reactive and, when ground sufficiently fine, may have potential as a cement component.

Trace Elements

Table 1 has been prepared to provide analysis of the extensively reported toxic and non-toxic element concentrations of SSA [2, 4, 12, 13, 17, 28, 30, 32, 34, 35, 42, 44, 45, 49, 55, 56, 58, 70-74, 76, 82, 83, 85, 87, 97, 100-104, 107, 108 and 111-132].

Although the most abundant elements present are Si, Ca, Fe, Al and P, the contents of toxic trace elements such as Zn, Cu, Cr, Pb, Ni and Cd are of greater importance concerning the environmental impact of the material use. It should be noted that the lower sample numbers available at times for abundant elements such as Si, does not reflect that these elements were only present in a small number of SSA samples, but rather that the researchers focused more on reporting the contents of the harmful trace elements.

Table 1 provides target limits set for these elements in Germany (Landerarbeitsgeselschaft Abfall (LAGA) document, 1994) for the use of wastes as construction materials and the data shows that the mean values of these elements for SSA are within the targets, with the exception of cadmium, which is marginally over. Two points in this context should be noted: (i) the reported values in Table 1 are simply target values and not the mandatory limits and (ii) the research suggests that the potentially harmful constituents of the SSA become effectively bound and encapsulated, when used in concrete.

Variability in element concentrations in SSA are evident from the high coefficient of variation results in Table 1 and can be partly attributed to differences in (i) waste water treatments systems, (ii) incineration conditions and (iii) method of testing (atomic absorption spectrophotometry (AAS) vs.

Table 1: SSA toxic and non-toxic element concentrations data from the literature

ELEMENT	SAMPLE NUMBER	MEAN mg/kg	S.D. mg/kg	CV %	GERMAN TARGET LIMITS mg/kg
Toxic					
Fe	23	68454	52037	76	-
Al	22	44885	27053	60	-
Zn	54	3355	4360	130	10000
Cu	56	2260	3701	164	7000
Ba	8	1997	725	36	-
Cr	47	750	1292	172	2000
Sr	5	435	171	39	-
Pb	52	373	502	135	6000
Ni	39	290	420	145	500
V	7	251	228	91	-
Co	8	200	227	113	-
Se	6	96	208	218	-
Sb	5	51	23	45	-
As	14	38	68	181	-
Cd	42	24	77	315	20
Hg	15	3	3	114	-
Non-toxic					
Si	8	113368	69872	62	-
P	21	60697	42802	71	-
Ca	15	54493	24451	45	-
Na	11	17126	26002	152	-
Mg	12	13894	6097	44	-
K	9	9756	3694	38	-
Ti	7	3344	3592	107	-
Mn	17	1404	831	59	-
Cl	19	434	533	123	-
Zr	7	378	296	78	-
Sn	7	182	187	103	-
Ag	9	166	129	78	-
Mo	20	36	38	104	-

inductively coupled plasma (ICP) tests). It is suggested that supplementary processing treatments such as ageing and acid washing can be utilized to regulate the contents of SSA, if so required.

Based on a mean chloride content value of 0.04% calculated from data in the literature, SSA generally complies with the limit of 0.1% set for both cement in EN 197-1 (2011) and the use of fly ash in concrete in EN 450 (2012), respectively, whilst EN 12620 (2013) requires the producer to declare the chloride levels for the use of aggregate in concrete.

As stated previously, the high aluminium content of SSA may also benefit resistance to chloride attack in concrete applications. Limited data on the sulphate content of SSA also appears to suggest that the material should also comply with the respective 3% limit given for fly ash in EN 450 (2012).

4. Use in Concrete Related Applications

4.1 Cement

Two areas of research on the use of SSA in cement have generally been considered, namely as: (i) as a raw feed for cement clinker manufacture and (ii) as a component of cement. The relevant standard on cement in Europe, EN 197 (2011), allows the specifier some flexibility to incorporate certain secondary materials such as granulated blast furnace slag and fly ash as main constituents and perhaps with future developments SSA can also be included. EN 197 (2011) also allows the use of up to 5% of “minor additional constituents” and as such there is potential for SSA to be incorporated in cement at this low content under this standard.

4.1.1 Raw Feed for Cement Clinker

SSA can contribute to SiO_2, Al_2O_3 and Fe_2O_3 requirements in the cement clinker production, whilst its CaO content may also lead to minor reductions in CO_2 emissions by lowering the calcareous material content.

The use of SSA has been explored at low contents from 1 - 11% [67, 69, 71-73, 104 and 133], though in one study [67], SSA had only been used in a single blend at a mere 1% and as such results from this publication are not included in the analysis. A number of review style papers [134-136], which referred to some of the above publications have also been identified in the literature. These review papers discussed the negative effects of heavy metals and phosphorus contents of SSA on cement performance and suggested pre-treatment of the material before use.

To analyse the trends associated with the use of SSA, a selection of key parameters for the eco-cement blends produced are presented in Table 2. Brief notes on the performances of the resulting cement mixes are also included. During these trials, the contents of other secondary materials such as fly ash, copper slag and dried sewage sludge, varied to satisfy the required oxide quotas. As such, it is difficult to directly quantify the impact of SSA, albeit certain trends can be observed from the data.

Table 2: Selected results on the chemical composition of clinker blends produced with SSA

REF	PARAMETER, %	SSA CONTENTS IN BLENDS				NOTES
		PC	2%	4%	8%	
[69]	P_2O_5	0.17	0.58	0.92	1.58	Blend: Limestone, sand, PFA and CS. The cement compound contents for the lower content SSA blends showed reasonable correlations to control mix. Though at higher SSA contents, it is likely that pre-treatment of the ash would be needed before use.
	SO_3	0.27	0.18	0.30	0.93	
	C_3S	50.0	38.9	30.9	19.3	
	C_2S	27.3	31.4	32.6	22.4	
		PC	6.8%	8.5%	9.3%	
[72/104]	P_2O_5	N/D	0.50	0.48	0.85	Blend: Limestone, WPSA, IWSA and ferrate. SSA blends 1 and 2 had long term strengths comparable to the control (but lower early age due to lower C_3S), though strengths were significantly lower for 3rd mix, with a higher P_2O_5 content.
	SO_3	2.03	0.41	0.38	0.45	
	C_3S	51.01	26.74	45.15	13.98	
	C_2S	23.21	46.08	26.55	54.05	
		PC	4.2%	4.7%	8.9%	
[73]	P_2O_5	N/D	0.21	0.46	0.75	Blend: Limestone, WPSA and ferrate. Setting times were closely related to C_3S %, increased for 1st and 2nd mix and decreased for 3rd mix relative to the control. Long term strengths were comparable to control, except for the 3rd mix with high P_2O_5.
	SO_3	2.03	3.51	3.24	3.27	
	C_3S	51.01	56.91	48.65	31.74	
	C_2S	23.21	17.07	24.20	42.47	
		PC	4.9%	6.5%	11.39%	

[71]	P_2O_5	N/D	0.21	0.46	0.75	Blend: Limestone, WPSA and ferrate The 1st and 2nd SSA blends showed similar strength performance and hydration products to the control mix, though the 3rd mix with large amounts of C_2S, underperformed with lower compressive strengths.
	SO_3	2.2	0.14	0.34	0.37	
	C_3S	46.71	56.91	48.65	35.6	
	C_2S	27.33	17.07	24.2	38.37	

N/D = Not detected, PC = Portland cement clinker, PFA = pulverised fuel ash, CS = copper slag, WPSA = water purification sludge ash, IWSA = industrial wastewater sludge ash

At SSA contents of up to 6%, though both increases and decreases in C_3S and C_2S contents are evident with increasing SSA, the impact on the observed mechanical performance are minimal and long term strength comparable to reference PC blends have been achieved, indicating that SSA appears to be a feasible option at this level of inclusion.

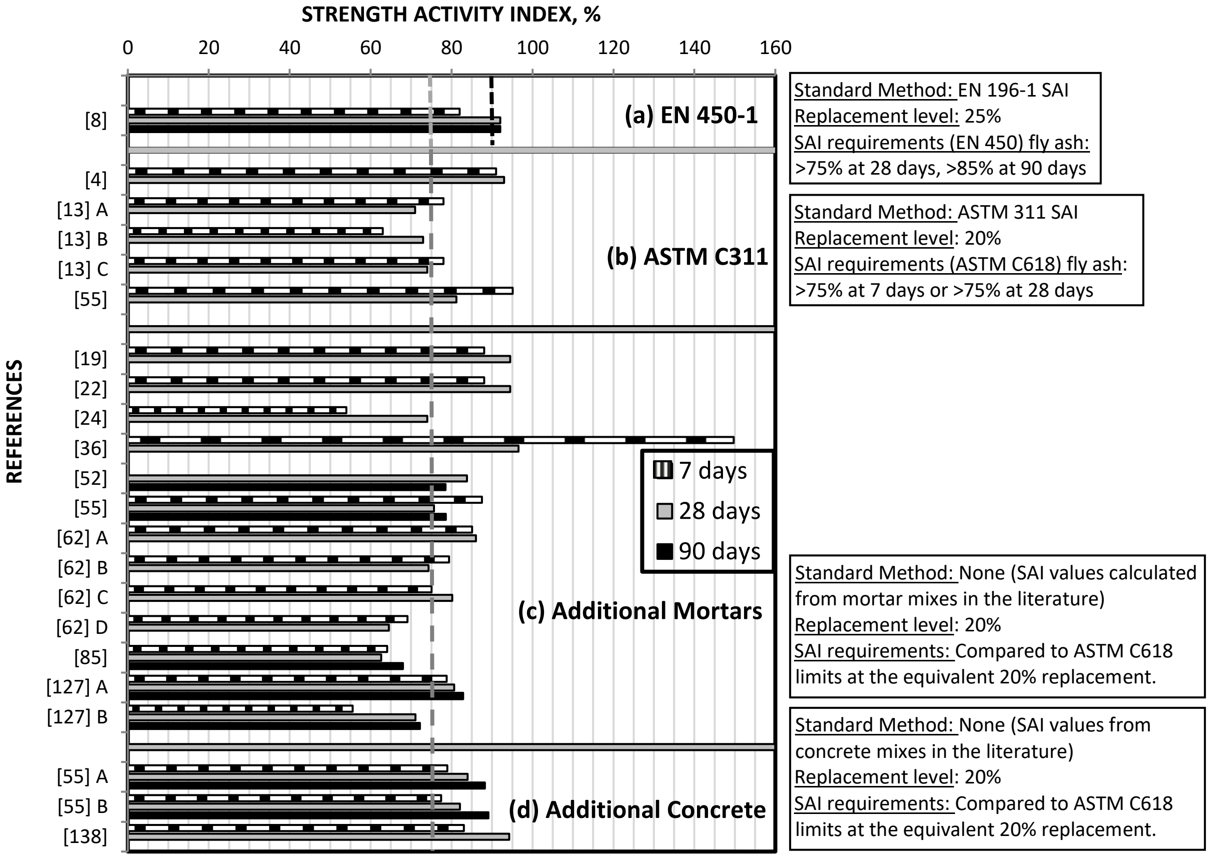
At higher SSA contents, up to 11%, the contents of heavy metals, sulphates and in particular phosphorus, becomes excessively high, resulting in an increase in setting times and the suppression of strength development. Treatment of SSA to extract phosphorus before use does appear to be a sensible option, given the negative impact this mineral has on cement performance and how it can serve as a valuable resource for agricultural purposes.

The phosphorus content of SSA samples used in the above studies varied from 7 - 9%, which is actually lower than the average value of 12.6% calculated based on all SSA samples in the literature, with a content range of 0.25 - 32%. As such, before considering use in this application, the phosphorus content of the material should be taken into account.

The use of dried sewage sludge is a potential alternative, though, there is less control of the chemical composition of the material in this state and as such, it may have more limited applications. However, there is no incineration treatment involved and the dried sludge has a higher calorific value due to the organic matter content, which would reduce the energy requirements in the cement production process.

4.1.2 Cement Component

As a cement component, the pozzolanic activity of SSA in ground form is one of the principal factors affecting its potential for use. This property of SSA is assessed from strength activity index (SAI) tests and measuring the quantity of $Ca(OH)_2$ fixed. The reported results from standard SAI tests undertaken based on the procedures in EN 450 and ASTM C311, which were originally adopted for testing fly ash, are presented in Figure 4. Though not specifically in strict accordance with these standards, SAI values calculated at a 20% SSA replacement level from additional mortar and concrete mixes tested in the literature are also displayed in Figure 4.



Standard Method: EN 196-1 SAI
Replacement level: 25%
SAI requirements (EN 450) fly ash: >75% at 28 days, >85% at 90 days

Standard Method: ASTM 311 SAI
Replacement level: 20%
SAI requirements (ASTM C618) fly ash: >75% at 7 days or >75% at 28 days

Standard Method: None (SAI values calculated from mortar mixes in the literature)
Replacement level: 20%
SAI requirements: Compared to ASTM C618 limits at the equivalent 20% replacement.

Standard Method: None (SAI values from concrete mixes in the literature)
Replacement level: 20%
SAI requirements: Compared to ASTM C618 limits at the equivalent 20% replacement.

Figure 4: Strength activity index results as a measure of the pozzolanic activity of SSA

In the standard tests, SSA mixes generally satisfied the respective limits outlined for fly ash of SAI values greater than 75% at 7 or 28 days in ASTM C618 (2008) at the 20% replacement level and greater than 75% and 85% SAI values at 28 and 90 days respectively for a 25% replacement level in

EN 450. Similarly for the additional mortar and concrete mixes, the majority complied with the respective ASTM C618 limit.

Though not surprisingly, the rate of strength development at up to 90 days is lower for SSA mixes than the corresponding control PC mixes, with the exception of one study [36] which can be singled out as an anomaly. Indications of typical pozzolanic behaviours of lower early strength and greater later age gains are also evident in the SSA mix results from many studies (Figure 4).

Measures of $Ca(OH)_2$ fixed by the pozzolanic activity SSA have been determined through saturated lime tests [8], Frattini tests [8] and thermogravimetric analysis [52 and 53], showing that significant pozzolanic reactions occurred with SSA, which increased with curing age and SSA content and again were at a level comparable to fly ash.

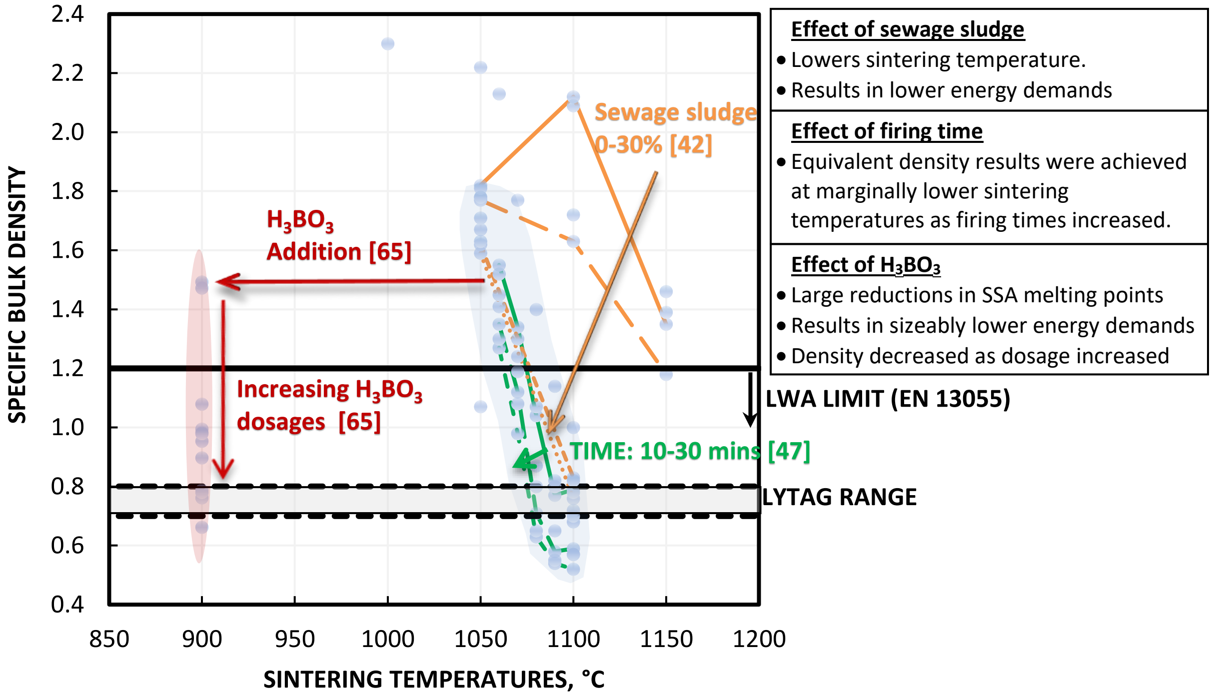
Though the results suggest that SSA can perform as a capable cementitous component, additional experiments to further enhance its performance have also been undertaken. Nanomaterials additions were effective in improving the microstructure and density of cement pastes containing SSA, resulting in improved mechanical performance [110, 139 and 140]. It is also expected that other materials such as silica fume or metakaolin could be used effectively alongside SSA, perhaps in high performance concrete. Silica fume would be the preferred option given that it is more chemically compatible due to its lack of alumina that could be compensated by SSA. Calcination treatment, involving the heating of SSA at temperatures ranging from 700 - 1200°C, has also been shown as an effective method of increasing the amorphous content of the material and consequently enhancing the pozzlanic activity [24]. SAI values on par with control PC mixes have been achieved at up to 28 day curing times, after SSA had been heated from 1000 - 1200°C.

4.2 Aggregate

The characteristics of SSA, specifically its fineness, suggest that the material may be suitable for use in concrete as filler or fine aggregate. The reported performance of concrete using SSA in this form [7, 14, 17, 35 and 53] is covered in Section 4.3 below.

SSA also has good prospects as a manufactured lightweight aggregate and many attempts have been made in the literature to exploit this potential application [28, 42, 47, 48, 65, 66, 97, 109, 141-144]. The process typically involves pelletizing and sintering at high temperatures to produce high porosity aggregates that retain strong surface layers.

Mechanical and lightweight properties of manufactured SSA aggregates are strongly connected to the sintering conditions. Indeed, bulk density results after sintering at temperatures from 900 - 1150°C are presented in Figure 5 [47, 42, 65 and 109]. At 1050°C, expansion processes begin to form resulting in large discontinuous irregular pores, which leads to a sharp decrease in density and strength of the manufactured aggregates.



Effect of sewage sludge

- Lowers sintering temperature.
- Results in lower energy demands

Effect of firing time

- Equivalent density results were achieved at marginally lower sintering temperatures as firing times increased.

Effect of H_3BO_3

- Large reductions in SSA melting points
- Results in sizeably lower energy demands
- Density decreased as dosage increased

Figure 5: Bulk density of manufactured SSA lightweight aggregate

At temperatures above 1070°C, SSA aggregates fall within the lightweight aggregate classification limit of 1200 kg/m^3 set in EN 13055-1 (2002) and are comparable to Lytag aggregate at temperatures from 1080 - 1100°C. Increasing the sintering time, one example of which is highlighted [47] in Figure 5, also leads to a sharper decrease in bulk density.

The effect of additions of sewage sludge [42], boric acid (H_3BO_3) [65] and glass cullet powder [97] in the production process have also been investigated. As shown in Figure 5, sewage sludge and in particular H_3BO lowers the melting points of the mix, while similar behaviour is also evident with glass cullet additions [97], thus the expansive processes and resultant weight losses are initiated early, resulting in lower energy demand.

The lightweight properties of the aggregate also need to be balanced with its strength performance. Strength has been found to increase up to a maximum at the melting point temperature of SSA (at approximately 1050°C) as the aggregate microstructure becomes well formed and dense. At higher temperatures, the strength decreases as apertures are formed. When the bulk density is comparable to Lytag aggregate, equivalent compressive strengths from 3 - 5 MPa [142] have been achieved for the SSA aggregate, which falls at the lower end of the expected Lytag range. It has also been shown that additions of clay, aluminium oxide and municipal solid waste fly ash are effective options to enhance strength [97 and 142] and can be incorporated to tailor the end properties of the manufactured lightweight aggregates from SSA.

4.3 Mortar and Concrete

4.3.1 Use as Aggregate

This use has been reported as both in the form of fine and filler aggregate components, typically at moderately low contents [7, 14, 17, 35 and 53].

The limited research undertaken [7 and 53] reports of large reduction in workability or large increases in water contents of concrete with the use of a small proportion SSA as the sand component (up to 15%) because of the alleged effect of higher than normal porosity/absorption characteristics. However, it would appear that mix design has not been revised in these studies to accommodate the SSA characteristics. Furthermore, were the water demand to still increase, a water reducing admixture can be used to compensate for this deficiency.

The introduction of SSA has led to reduction in the concrete mix density in certain cases [14 and 17], which would usually be expected given that the material density is comparable to light sand. Though in one particular case, the replacement of 10% of the denser control limestone aggregate with SSA resulted in an increase in the mix density [53] and this was attributed to the beneficial effect of the fine particles of SSA on the particle packing in the concrete mixture.

Reported compressive strength data would initially appear to be at odds showing both decreases [17 and 35] and increases [14 and 53] with the inclusion of SSA, but this comes down to how this material has been adopted in the mix design. Indeed, this is a very common phenomenon with the evaluation of new materials for their use in concrete and for this reason the data reported often require a very careful examination. Nonetheless, on balance it would appear that any impacts of low contents of SSA on compressive strength performance are not major either way and are manageable. Flexural and tensile strength behaviours have been found to match up well with equivalent compressive strength results [14, 17 and 35].

Capillary water absorption coefficients ranging from 0.26 - 0.9 $kg/m^2\ h^{0.5}$ have been reported for concrete mixes containing up to 20% SSA [14 and 53], compared to non-SSA control values ranging from 0.55 – 0.61 $kg/m^2\ h^{0.5}$. Some level of absorption increase is expected with more porous aggregates, though the use of SSA at up to 20% does not flag any particularly negative durability effects, as these absorption coefficient values are within the normal range for conventional concrete mixes.

Skid resistance results for concrete slabs containing up to 40% SSA as fine aggregate have been comparable to and, at times, outperformed the control normal sand mix [35]. This is likely due to the irregular nature of SSA particles and indeed, all SSA mixes are reported to be above the minimum skid resistance requirements outlined in ASTM E303 (1998).

4.3.2 Use as Binder

As a cement component in ground form, research on the effects of SSA on fresh properties of mortar and concrete mixes included workability and setting time testing. No problems relating to segregation or bleeding have been reported.

Results from flow table spread tests on mortars, presented in Figure 6 as the percentage change from the control, point to reductions in workability with a like-for-like replacement of cement with SSA [13, 21, 37, 55, 62, 145 and 146]. The average rate of decrease in workability calculated is 6% for every 10% SSA and equivalent slump reductions of 12% per 10% SSA have also been determined for concrete mixes [21, 27, 55 and 138]. Whilst this data provides an informative benchmark for SSA performance in fresh mortar/concrete, the specifier should perhaps seek to adjust the mix design to accommodate the characteristics of the material, possibly with the use of water reducing admixtures to achieve satisfactory workability and the results suggest that this is very doable at low SSA contents.

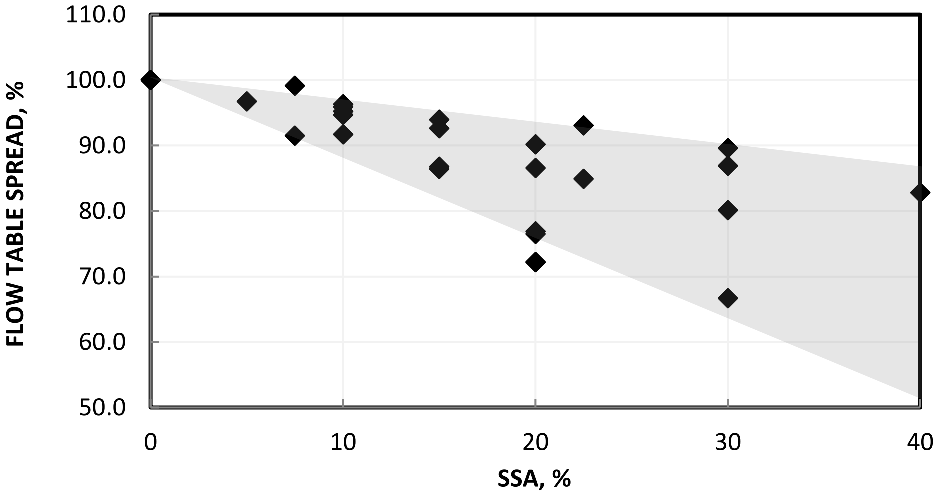


Figure 6: Effect of SSA as cement replacement on mortar workability

Setting times lengthen with increasing SSA contents [22, 40 and 138], with an average increase of 35% per 10% replacement calculated for both the initial and final setting times. Longer setting times are to be expected when using pozzolanic materials and the introduction of SSA causes no difficulties relating to the requirements of EN 197-1 (2011) for common cements, in which an initial setting time greater than 45 minutes is stated.

Data on the effect of SSA on compressive strength (28 days) presented in Figure 7, shows reduction with increasing SSA content, on average at the rate of 1 for 1% SSA replacement of Portland cement clinker. Lower early age strengths are typical for pozzolanic materials, though an average compressive strengths of 92% of the control at 90 days [52, 53, 55 and 137], suggests a positive strength contribution from SSA in the long term. It has also been shown that SSA can be used at lower contents and achieve strength comparable to the control using a variety of mix design adjustments, including increasing the cement content [15], using superplasticizer to lower w/c ratio of the mix [4, 13 and 43], nano-materials additions [40] and increasing the fineness of SSA [21 and 81].

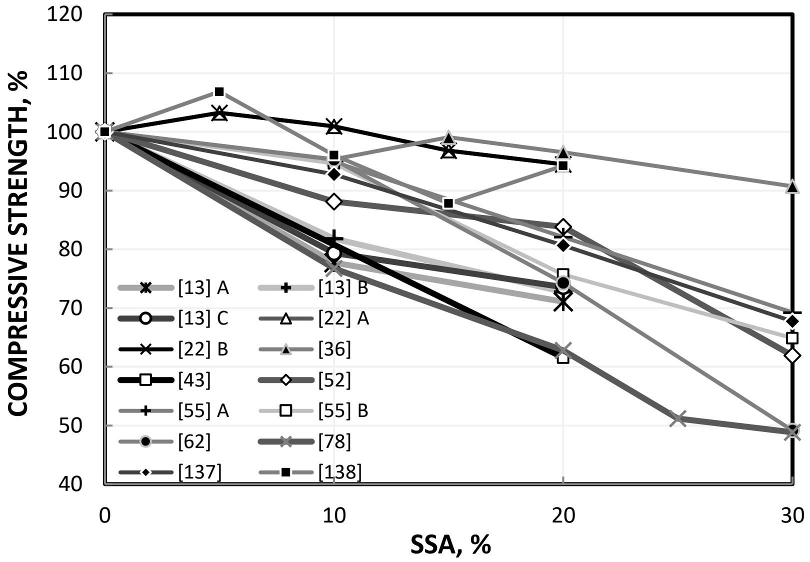


Figure 7: Effect of SSA replacement level as a cement component on 28 day compressive strength

Reported tensile and flexural strength data emulate the compressive strength results [5, 22, 37, 46, 62, 78, 81, 137, 146 and 147], with reduction evident as SSA content is increased, though this became proportionally less with age. Importantly, the data also suggests that the relationship established between flexural and compressive strength in Eurocode 2 (EN 1992-1-1, 2004) is equally valid for concrete mixes containing SSA.

Limited research has been undertaken on the effect of SSA on deformation properties of concrete such as modulus of elasticity [11] and shrinkage [27, 62, 86 and 148], which indicates that the development of the material use is still at an early stage. Elastic modulus results were found to be somewhat inconsistent [11], however, previous strength data suggests that reductions in the modulus of elasticity may occur with SSA. Marginal reduction in drying shrinkage is evident in SSA mixes [27, 62, 86 and 148], though at SSA contents less than 20%, the overall effects appear to be negligible.

The effect of SSA on permeation properties of mortar/concrete, is reported as resulting in a decrease in absorptivity [53, 36, 138 and 27] and permeability [138], which is somewhat surprising and is at odds with the reported increase in porosity [137, 36 and 62]. One option to ease possible durability concerns due to higher porosity would be to use a composite cement in conjunction with SSA, using materials such as fly ash, metakaolin and silica fume to plug pore spaces.

Corrosion resistance has been found to improve for SSA contents up to 20%, though for higher contents up to 60%, resistance lower than the control have been reported [137]. It would appear that two opposing factors are at play: the positive effect of chemically binding of chlorides due to the aluminium content of SSA is the overriding influence at low content, whilst, at high SSA content, the continued weakening of the pore structure from increased porosity and reduced hydration leads to net negative effects on durability. As such, at recommended lower contents of SSA, the impacts on corrosion resistance should be positive. Increased carbonation rates have also been reported [137], which is to be expected for all mixes incorporating pozzolanic materials as cement component.

Tests on susceptibility to sulphate attack revealed no significant expansion [62], suggesting that the sulphates present in SSA are not in soluble form to react with tricalcium aluminates to cause damaging expansive processes. Le Chaterlier soundness tests on mortars containing up to 20% SSA have also been shown to satisfy the recommended British Standard limits [22].

4.4 Blocks

The use of SSA, both in the form of fine aggregate [53 and 149] and cement component [31 and 53] in concrete blocks appears to be a good fit, given the large market and generally less demanding strength requirements.

As fine aggregate, two main findings emerged:

- Blocks produced with a 10% addition of SSA as aggregate had greater strength, higher density and lower absorption properties compared to the control. Though this appears to be somewhat contradictory to previous findings with SSA, the improvements have been attributed to the filling effects of the fine particles of SSA [53].

- Up to 35% SSA could be included as aggregate and still satisfy a target 20 MPa strength requirement. This could be increased to 40% in air entrained and water reduced concrete mixes and indeed as reported in section 5. Case Studies, using blocks with this mix design, had been used in a field study as erosion control structures in Long Island, USA. After 12 months of monitoring, no weathering or deterioration of the blocks was evident [149].

As a cement component, the findings emerging from the literature are as follows:

- Precast blocks containing up to 20% SSA demonstrated remarkably low degree of variability and high repeatability. The dimensional stability and configuration of the SSA blocks are within the allowable tolerances, the coefficient of variation of the apparent and water saturated densities were very small (maximum of 0.008) and the compressive strength standard deviations for the 20% SSA blocks were below the control blocks (7% compared to 10% for the control blocks) [31].

- As a cement replacement at contents up to 20%, changes in the density and compressive strength relative to the control mixes were very manageable (up to 4% and 6% reductions respectively), whilst SSA merely caused marginal differences in the water absorption and thermal properties. As an addition by weight of cement at contents up to 10%, no substantial change in strength has been reported, whilst somewhat surprisingly, reduction in the water absorption and capillary water absorption occurred [53].

4.5 Lightweight Aggregate Concrete

The relationship between density and strength [26, 47 and 48] of concrete made with coarse SSA lightweight aggregate (except one where both coarse and fine were SSA lightweight aggregate) is shown in Figure 8, together with results of the corresponding reference mixes made with commercially available Leca (lightweight expanded clay aggregate).

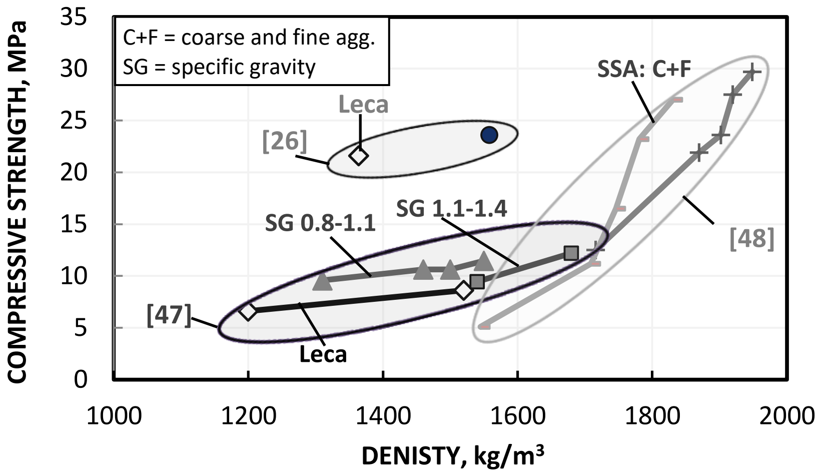


Figure 8: Compressive strength (28 days) and density behaviour of concrete mixes containing lightweight SSA aggregate

The SSA lightweight aggregate concrete mixes achieved strength (28 days) suitable for structural application, reaching up to 30 MPa. Strength greater than the Leca aggregates mixtures have been reached, though SSA mixes generally had higher densities, but most remained within the lightweight concrete guidelines i.e. less than 1850 kg/m^3.

As shown [47], the separation of SSA aggregates based on weight, i.e. specific gravities of 0.8 - 1.1 and 1.1 - 1.4, can be an effective method of improving the lightweight properties of concrete, without compromising strength. The research shows that a great deal of flexibility can be achieved in the use of SSA lightweight aggregates, in terms of desirable strength and lightweight properties with adjustments of the sintering process, mix design (fine:coarse aggregate ratio) and the use of additional materials such as clay in the aggregate manufacturing process [150].

Absorption values of approximately 10%, which is typical for lightweight aggregate concrete, have been reported for SSA mixes [26 and 48]. The pelletizing process also produced more rounded and smoother SSA aggregates which in fact led to workability improvement [48 and 151] rather than the reduction that has previously been reported in other concrete applications. Thermal conductivity ranging from 0.27 - 0.49 W/m°C [26 and 48] has been reported for lightweight concrete panels containing SSA. This property improved as density decreased and it would appear that the material can be used to meet the lightweight aggregate concrete requirement of 0.43 W/m°C specified in ASTM C332-87.

4.6 Aerated Concrete

SSA appears suited for use in aerated concrete, as its high aluminium content and porous nature can contribute to delivering the desired lightweight and thermal properties. Although of filler fineness, the material has been used as replacement of cement [25, 38, 98 and 152] and PFA [153] to enhance the lightweight characteristics and thermal properties, rather than for its potential pozzolanic activity.

A group of the same authors [25, 38, 98 and 152] have used SSA in bulk quantities (up to 80% by weight of cement) in “lightweight foamed materials” mixes. The process of casting the cubes, demoulding, curing and cutting away any excess bulging, is symptomatic of aerated concrete production rather than foamed concrete, which typically involves the addition of premade foam to a base mix.

Compressive strength results (28 day) are presented in Figure 9 [25, 38, 98 and 152] for mixes with SSA contents from 60 - 80%, aluminium powder dosages from 0.1 - 0.3% and water/solids (w/s) ratios from 0.5 - 0.8, where solids represents the sum of cement and SSA. It appears that SSA content had the greatest impact on strength, though the effect of both SSA and aluminium powder is more pronounced at lower w/s ratios. It is encouraging that mixes with high SSA contents can comfortably satisfy the minimum strength limit of 1.5 N/mm^2 of EN 771-4 (2011) for autoclaved aerated concrete masonry units.

Increasing the SSA and aluminium powder contents both led to higher porosity which improved the thermal and lightweight properties of the products. Specific gravity from 0.6 – 1.0 and thermal conductivity from 0.09 – 0.24 W/mK have also been achieved. The net density of autoclaved aerated concrete is usually between 300 and 1000 kg/m^3, according to EN 771-4, whilst thermal conductivity

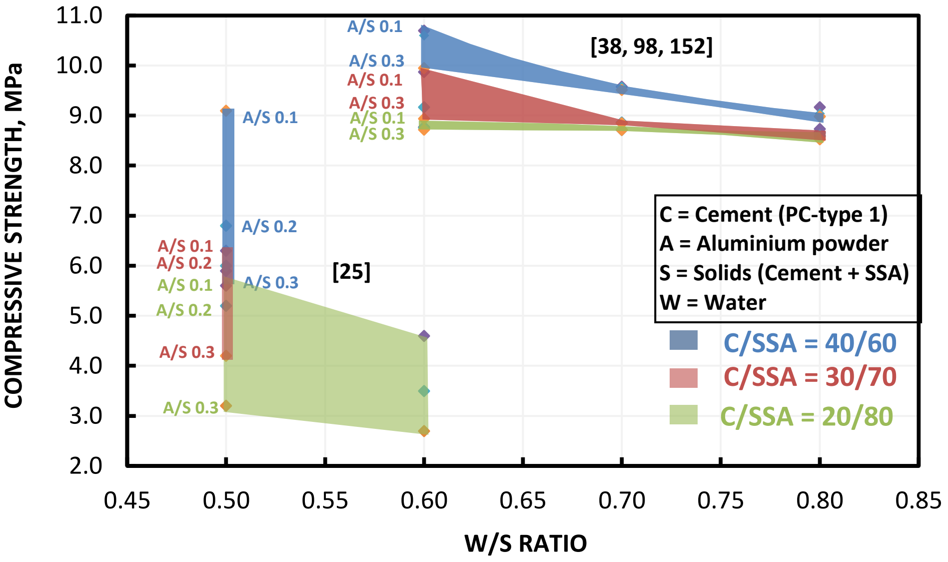


Figure 9: Compressive strength behaviours of SSA aerated concrete mixes

requirements of 0.12 - 0.15 W/mK have been reported in Taiwanese Standards [133], both of which are achievable with SSA mixtures.

Interestingly, case studies have been carried out by aerated concrete producers using SSA as a substitute for PFA and as reported in section 5. Case Studies, blocks that were fit for use have been produced, though higher water contents were required in the production process [153].

4.7 Foamed Concrete

Foamed concrete is produced with the addition of pre-formed foam into a base mix of sand, cement and water. The mixtures have high flowability, self compacting, self curing, lightweight, low strength properties and have recently grown in popularity as fill material. SSA appears to be a suitable candidate for use, though this has not yet been explored to a great extent.

Based on the limited available data, the effects of SSA at 50% and 100% of the fine aggregate in foamed concrete mixes [13] are shown in Figure 10. The use of SSA led to improvement in strength (up to 70% increase) due to the filling effect from higher fines content, despite the increase in permeability of the resulting mixes. The thermal properties improved (lower thermal conductivity) due to the porous nature of SSA. Required flowability and self-compacting characteristics were maintained, despite some reductions in workability that have been reported.

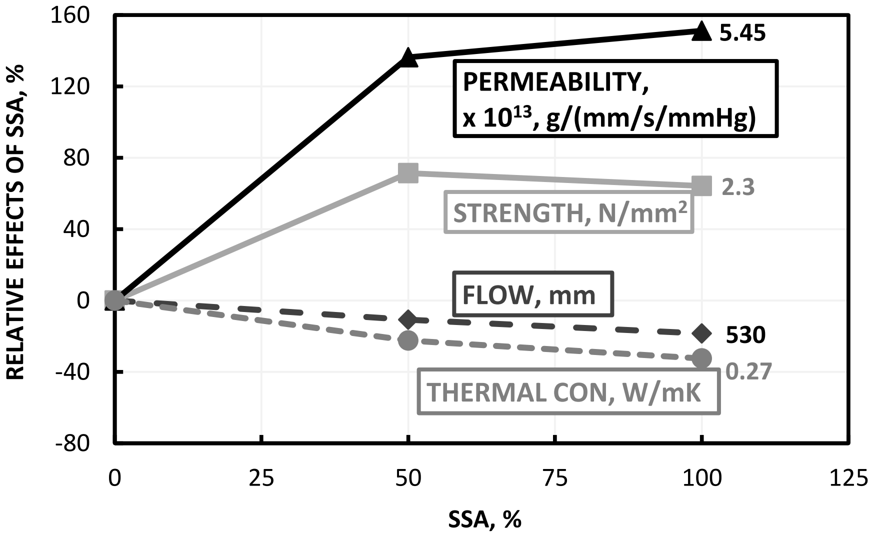


Figure 10: Effects of SSA as fine aggregate on foamed concrete properties [13]

4.8 Controlled Low Strength Materials (CLSM)

Controlled low strength materials (CLSM) are also becoming more prevalently used as backfill material. Low strength is required to facilitate future excavations, along with flowable consistence, self compacting and self curing properties. The American Concrete Institute guidance report (ACI 229R-5) recognises Portland cement and fly ash (as filler) as the conventional materials used alongside coarse and fine aggregate. Suitable nonstandard materials are permitted, though SSA is not mentioned in name, as research on the material is only at the early stages.

Some initial work has been carried out [154-156] using SSA as filler material, with cement contents from both ends of the spectrum expected for CLSMs (20 kg/m^3 – 120 kg/m^3). Crushed stone powder (CSP) has also been used in place of sand in a number of mixes [154-156].

To achieve the target flowability, SSA mixes required higher water contents compared to the control fly ash mixes, which is expected given the benefits of the ball bearing effect of fly ash on workability. The bleeding rate also increased in the SSA mixes, though this can be partly offset with the use of CSP in place of sand and by decreasing the filler/aggregate ratio.

Compressive strength results at 28 days from the three studies are presented in Figure 11. According to ACI 229R (1999), strengths less than 2.1 MPa and 0.3 MPa are desired to allow for machine and manual excavation, respectively. At low and moderate cement contents, SSA mixes with and without CSP, appear suitable for manual excavation applications, with strength comparable to the control fly ash mix. The strength reduction relative to the control fly ash mix, becomes more significant at high cement contents, though in areas lacking available fly ash, SSA can perhaps serve as a workable alternative, that is comparable to well compacted soil, in machine excavation applications.

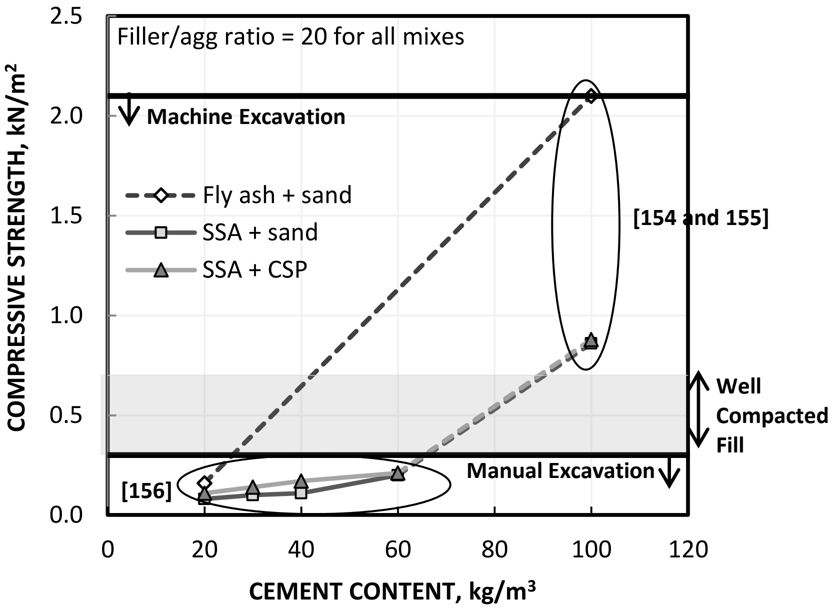


Figure 11: Compressive strength performance of CLSMs containing SSA as filler material

5. Case Studies

The practical applications of SSA appears to be still very much in its early stages, though perhaps private organisations undertaking work of this nature are reluctant to release the information publically. However, the limited reported case studies are judged to be encouraging for developing the use of SSA in concrete and concrete related products and are briefly described in Table 3.

Table 3: Case studies on the use of SSA in concrete related applications

REF	YEAR	DESCRIPTION	FINDINGS
[15]	2007	Concrete: SSA used as replacement of coal fly ash for up to 1/3 of the cement.	Satisfactory strength was achieved with marginal higher cement content. Suggests that < 50% of fly ash can be replaced by SSA.
[33]	2012	Concrete: SSA as replacement of up to 20% of sand in pavers.	SSA mixes met requirements, though marginal cement increases were needed to achieve equal strength.
[43]	2002	Concrete: SSA used as 10% (with coal fly ash) and 20% cement components.	Strength similar to the control achieved by using superplasticizer and lowering the w/c. Increased shrinkage has been reported.
		Blocks: SSA as 10% replacement of coal bottom ash in medium density blocks	Problems occurred in the production and the blocks were not suitable for testing.
[149]	2002	Blocks: 40% SSA as fine aggregate used in erosion control structure.	No weathering or damage over 12 month monitoring period. SSA blocks performed comparable to control blocks.
[153]	2007	Aerated concrete: SSA as partial substitute for fly ash by two producers.	Products have been successfully produced that were fit for use, though the higher water content demands raised concerns.
[155]	2011	CLSM: SSA used in CLSM in backfill construction.	Excellent performance as backfill material has been reported.

Indeed, the reported findings are, for the most part positive, though there have been some issues that can be expected when experimenting with a new product. In concrete mixes, performance similar to the control have been achieved with SSA, both as fine aggregate and in ground form as cement component, through modification of the mix designs, including superplasticizer addition with a lower w/c ratio or increased cement contents. Encouraging performance has also been achieved with SSA in the manufacture of normal weight concrete blocks, CLSM and aerated concrete, though the latter application highlighted the changes in the water demands when using SSA as a replacement of fly ash.

6. Further Research Opportunities to Enhance SSA Use

Suggestions are offered, identifying areas where the further research could benefit the potential use of SSA, including both ideas for new innovative applications and highlighting gaps in the current literature.

(i) **High performance concrete:** Though SSA in ground form may not be able to compete with fly ash or ground granulated blast-furnace slag as bulk replacement material for Portland clinker cement, it could add value when used in conjunction with ultrafine materials such as silica fume or metakaolin in high performance concrete. Of the two, silica fume seems most viable as (a) it is much finer and small proportion of SSA is unlikely to dilute the strength development, (b) a heavy dose of superplasticizer is required in concrete with silica fume anyway, therefore minor negative effects associated with SSA water demand will not be significant, (c) silica fume is chemically more compatible with SSA since it has virtually no alumina of its own and SSA contains approximately 14% Al_2O_3, (d) the reduced cost SSA in comparison to silica fume makes the SSA/silica fume option economically attractive.

(ii) **Concrete produced from composite cement:** Although some research has been carried out on use of SSA in combination with fly ash, this area can be strengthened to develop practical blends with fly ash and GGBS, with the aim to optimize engineering performance of concrete, whilst maximising the use sustainable materials.

(iii) **Foamed concrete, aerated concrete and CLSM:** SSA has shown an initial promise for use in these three related lightweight, low strength applications and further research could benefit the development of the material application in these areas.

(iv) **Concrete/mortar properties:** There is limited information available on the effect of SSA on the durability and load-dependent and load-independent deformation performance in mortar and concrete mixes and further work in these areas could improve the prospects for the material use.

(v) **Case studies:** An increase in the number of case studies available would assist in promoting confidence and familiarity with SSA and greatly benefit its practical application.

7. Conclusions

An extensive systematic analysis and evaluation of published literature on the application of SSA in concrete and concrete related products revealed that the material has considerable potential for use in several different forms: as raw feed in cement clinker and lightweight aggregate production, fine aggregate, filler aggregate and in ground form as cement component. The implied suggestion of this is that realisation of these outlets should lead to the consumption of SSA produced worldwide. The specific conclusions are presented as follows:

i. SSA has a porous microstructure with a density comparable to light sand and consists of irregularly shaped particles that predominantly fall in the silt and fine sand size fractions, suggesting suitability as fine aggregate or filler aggregate in concrete. In ground form, the material's oxide composition and amorphous content indicates potential suitability for use as a cementitous material. Due to the very nature of SSA, toxic elements are present in trace amounts, though the contents are generally below target limits for construction materials.

ii. As raw feed in cement clinker production, SSA can be used at low contents and achieve performance comparable to control Portland cement clinker blends. At marginally higher contents, treatment of the material to extract phosphorus appears to be a reasonable option that removes inhibiting effects on strength and setting behaviour. Furthermore, the phosphorus removed can also serve as a valuable resource for agricultural purposes.

iii. As fine aggregate and filler aggregate components in mortar and concrete, the effects on strength performance appear to be manageable at low SSA content up to 15% and through revision of the mix design to accommodate the characteristics of the material, perhaps including water reducing admixtures, satisfactory workability can also be achieved.

iv. As a cementitious component, SSA satisfies the standard pozzolanic activity measures in the majority of cases and in this regard is comparable to fly ash. In mortar and concrete mixes, using SSA as a direct cement replacement results in lower strength and workability, though at low contents, performance on par with the control can be achieved by adjusting the cement content or using superplasticizer to lower the w/c ratio of the mix. Nano-materials addition and increasing fineness can also further enhance strength. Regarding durability, the impacts on corrosion resistance at low SSA content appears to be positive, the carbonation rate increases as is expected for all mixes using pozzolanic materials and no significant expansion occurs during sulphate resistance testing.

v. The porous nature of SSA makes the material a good prospect for use in a range of lightweight applications, both in as-produced and ground form. A great deal of flexibility can be achieved in the performance of concrete made with manufactured SSA lightweight aggregate through adjustments of the sintering process and mix designs, with strengths suitable for structural applications attainable, along with lightweight properties comparable to commercially available Leca mixes. SSA can be used in bulk quantities in CLSM, as well as in aerated and foamed concrete and can satisfy the low strength, workability, lightweight properties and thermal requirements of the respective products.

vi. Limited case studies reported in the literature indicate promising performances using SSA in the production of concrete, normal weight and aerated blocks and controlled low strength materials, though the development of the practical application of the material can only be considered at present at the initial stages.

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Table captions

Table 1: SSA toxic and non-toxic element concentrations data from the literature

Table 2: Selected results on the chemical composition of clinker blends produced with SSA

Table 3: Case studies on the use of SSA in concrete related applications

Figure captions

Figure 1: Particle size distributions of (a) as-produced SSA with overall sand limits in concrete (BS 882) and (b) ground SSA with PC and fly ash samples.

Figure 2: Rate of publication of the oxide composition data on SSA

Figure 3: Ternary plot of SiO_2, Al_2O_3 and CaO contents for SSA

Figure 4: Strength activity index results as a measure of the pozzolanic activity of SSA

Figure 5: Bulk density of manufactured SSA lightweight aggregate

Figure 6: Effect of SSA as cement replacement on mortar workability

Figure 7: Effect of SSA replacement level as a cement component on 28 day compressive strength

Figure 8: Compressive strength (28 days) and density behaviour of concrete mixes containing lightweight SSA aggregate

Figure 9: Compressive strength behaviours of SSA aerated concrete mixes

Figure 10: Effects of SSA as fine aggregate on foamed concrete properties [13]

Figure 11: Compressive strength performance of CLSMs containing SSA as filler material.