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

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32 **Abstract**

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

41

42 **Key Words:** Sewage sludge ash, Systematic review, Concrete

43

44 **Highlights:**

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

50

51

52

53 **1. Introduction**

54 Sustainable waste management has been incorporated as a core principle in European (EU Directive
55 2008/98/EC on waste) and worldwide (United Nations Framework Convention on climate change,
56 1992) legislation. A more environmental friendly hierarchy of waste treatment options, of which
57 recycling and incineration rank above disposal, is now prescribed by law.

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

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

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

73 **2. The Project**

74 This paper examines the use of SSA in concrete and concrete related applications. A systematic
75 review of globally published literature in the English medium is undertaken, involving analysis,
76 evaluation and synthesis of data therein, covering the material's physical and chemical

77 characteristics and its use as raw feed for cement clinker and as cement components in producing
78 cement paste, mortar and concrete mixtures, as well as fine, filler and manufactured lightweight
79 aggregates.

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

84 **3. SSA Characteristics**

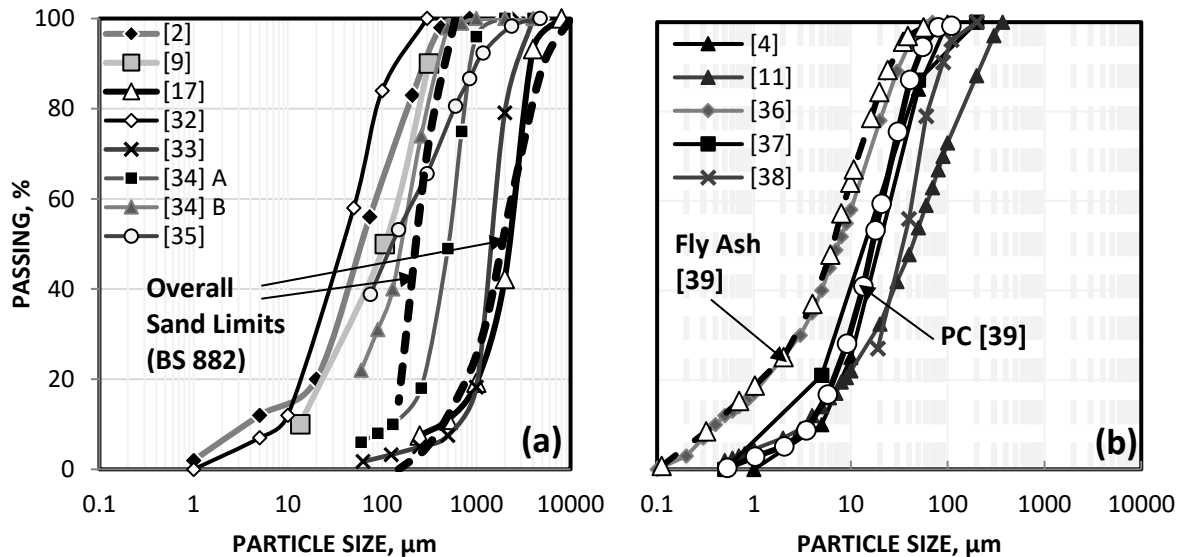
85 **Density**

86 The specific gravity of SSA has been found to range from 1.8 - 2.9, though the bulk of results were
87 skewed towards the upper end of this band with a mean value of 2.5 and standard deviation of 0.3
88 [2-26]. The material is somewhat comparable to light sand and less dense than Portland cement
89 (3.15). It has been shown that density increases with the incineration temperature, though the rate
90 of increase drops off above 1000°C. The low ratio of bulk density (average 805 kg/m³) [2, 8, 9, 17, 22,
91 23 and 26-28] to particle density is also indicative of the porous nature of SSA.

92 **Fineness and Grading**

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

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



99

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

102 SSA ground for use as a cementitious component (Figure 1b) can achieve well graded size
 103 distributions similar to Portland cement clinker (PC) and fly ash (class F). BET specific surface area
 104 and Blaine fineness however varied over a wide range from 2500 - 23100 m²/kg [4, 9, 11, 21, 24, 25,
 105 36 and 38] and 500 - 3900 m²/kg [4, 12, 21, 24, 31 and 40] respectively. The marked variability and
 106 discrepancies compared to typical Portland cement (e.g. BET 350 - 380 m²/kg [41]), suggest that
 107 these fineness measures are not ideally suited to assess SSA as a potential cementitious material,
 108 due to the effect of its irregular particle shapes and porous microstructure.

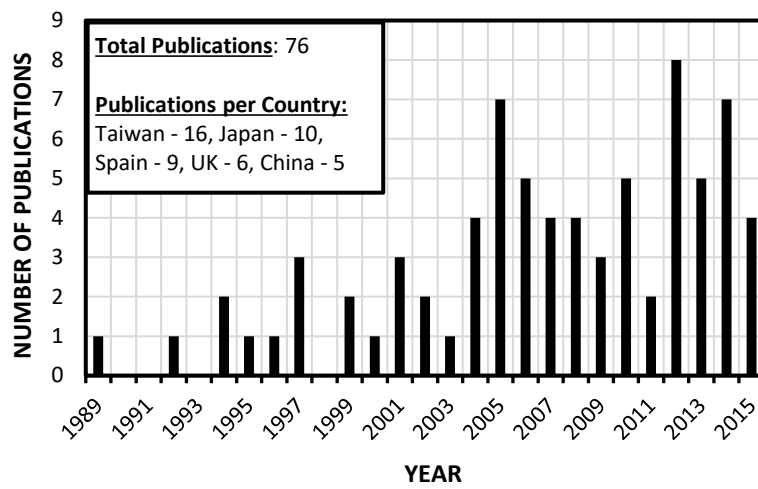
109 **Morphology**

110 SSA consists of irregular particles with rough surface textures and a porous microstructure [3, 4, 7,
 111 12, 13, 16, 17, 25, 31, 37, 38 and 42-46] which may lead to high absorption and an increase in the
 112 water demand of concrete using SSA. Indeed, water absorption values ranging from 8 - 20% have
 113 been reported [10, 13, 47 and 48], which is substantially higher than natural sand, which is typically
 114 1 - 3%. Superplasticizers are one option to consider as an admixture to counteract higher water
 115 demand resulting from the use of SSA in mortar and concrete.

116

117 **Oxide Composition**

118 The oxide composition of SSA has been widely reported [2, 7, 11, 13, 14, 16-18, 20, 22-24, 28, 31, 32,
119 34, 36-38, 40, 44, 45, 49-102]. A breakdown of publications produced per year is presented in Figure
120 2, showing that the data has been published over a period of 26 years, though as a sign of growing
121 interest in the use of sustainable materials, the majority of the research has been undertaken in the
122 last 10 years.



123
124 Figure 2: Rate of publication of the oxide composition data on SSA

125 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
126 others are present in smaller quantities. A ternary diagram of the main oxide contents is plotted for
127 157 SSA samples taken from the above 76 publications, in Figure 3, along with typical contents for
128 more established cementitious materials. The calculated mean, standard deviation (St Dev) and
129 coefficient of variation (CV) values for SiO_2 , Al_2O_3 and CaO are also given. This Figure shows that the
130 majority of results fall around the latent hydraulic and pozzolanic regions, suggesting potential for
131 SSA use as a cementitious component in concrete.

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

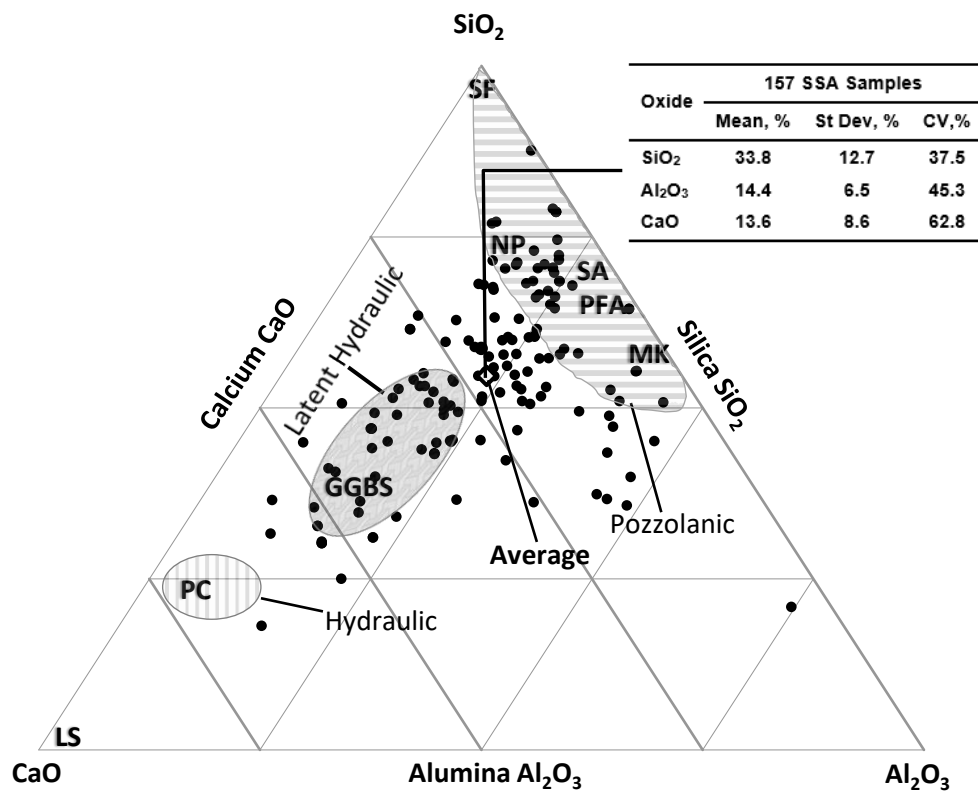


Figure 3: Ternary plot of SiO₂, Al₂O₃ and CaO contents for SSA

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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.

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

143 **Loss on Ignition (LOI)**

144 The LOI data for SSA obtained from the sourced literature yielded an average value of 3.5%, though
145 occasionally very high values up to 13% have been reported [2, 7, 12, 13, 15-17, 30, 31, 52, 64, 80,
146 81, 92, 94, 96, 103 and 104]. Thus, it is possible for SSA, as presently produced, to be generally able
147 to comply with the LOI limit of 5% set for cement in EN 197 (2011) and fly ash for concrete in EN 450

148 (2012). Where SSA is earmarked for specific use in concrete, a thorough burn during incineration
149 should be able to control the LOI.

150 **Mineralogy**

151 Quartz and hematite have been identified as the most abundant minerals in SSA, while many other
152 iron oxides, iron phosphates, calcium phosphates and aluminium phosphates have been reported to
153 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
154 and 105-110]. The amorphous content of SSA ranged from 35 - 75%, which suggests that the
155 material is somewhat reactive and, when ground sufficiently fine, may have potential as a cement
156 component.

157 **Trace Elements**

158 Table 1 has been prepared to provide analysis of the extensively reported toxic and non-toxic
159 element concentrations of SSA [2, 4, 12, 13, 17, 28, 30, 32, 34, 35, 42, 44, 45, 49, 55, 56, 58, 70-74,
160 76, 82, 83, 85, 87, 97, 100-104, 107, 108 and 111-132].

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

167 Table 1 provides target limits set for these elements in Germany (Landerarbeitsgesellschaft Abfall
168 (LAGA) document, 1994) for the use of wastes as construction materials and the data shows that the
169 mean values of these elements for SSA are within the targets, with the exception of cadmium, which
170 is marginally over. Two points in this context should be noted: (i) the reported values in Table 1 are
171 simply target values and not the mandatory limits and (ii) the research suggests that the potentially

172 harmful constituents of the SSA become effectively bound and encapsulated, when used in
 173 concrete.

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

177 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
<u>Toxic</u>					
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	-
<u>Non-toxic</u>					
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	-

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

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

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

187 **4. Use in Concrete Related Applications**

188 **4.1 Cement**

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

196 **4.1.1 Raw Feed for Cement Clinker**

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

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

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

212 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 ₂ O 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 ₃ S	50.0	38.9	30.9	19.3	
	C ₂ S	27.3	31.4	32.6	22.4	
	PC	6.8%	8.5%	9.3%		
[72/104]	P ₂ O 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 ₃ S), though strengths were significantly lower for 3 rd mix, with a higher P ₂ O ₅ content.
	SO ₃	2.03	0.41	0.38	0.45	
	C ₃ S	51.01	26.74	45.15	13.98	
	C ₂ S	23.21	46.08	26.55	54.05	
	PC	4.2%	4.7%	8.9%		
[73]	P ₂ O ₅	N/D	0.21	0.46	0.75	Blend: Limestone, WPSA and ferrate. Setting times were closely related to C ₃ S %, increased for 1 st and 2 nd mix and decreased for 3 rd mix relative to the control. Long term strengths were comparable to control, except for the 3 rd mix with high P ₂ O ₅ .
	SO ₃	2.03	3.51	3.24	3.27	
	C ₃ S	51.01	56.91	48.65	31.74	
	C ₂ S	23.21	17.07	24.20	42.47	
	PC	4.9%	6.5%	11.39%		

[71]	P ₂ O ₅	N/D	0.21	0.46	0.75	Blend: Limestone, WPSA and ferrate The 1 st and 2 nd SSA blends showed similar strength performance and hydration products to the control mix, though the 3 rd mix with large amounts of C ₂ S, underperformed with lower compressive strengths.
	SO ₃	2.2	0.14	0.34	0.37	
	C ₃ S	46.71	56.91	48.65	35.6	
	C ₂ S	27.33	17.07	24.2	38.37	

213 N/D = Not detected, PC = Portland cement clinker, PFA = pulverised fuel ash, CS = copper slag,
 214 WPSA = water purification sludge ash, IWSA = industrial wastewater sludge ash
 215

216 At SSA contents of up to 6%, though both increases and decreases in C₃S and C₂S contents are
 217 evident with increasing SSA, the impact on the observed mechanical performance are minimal and
 218 long term strength comparable to reference PC blends have been achieved, indicating that SSA
 219 appears to be a feasible option at this level of inclusion.

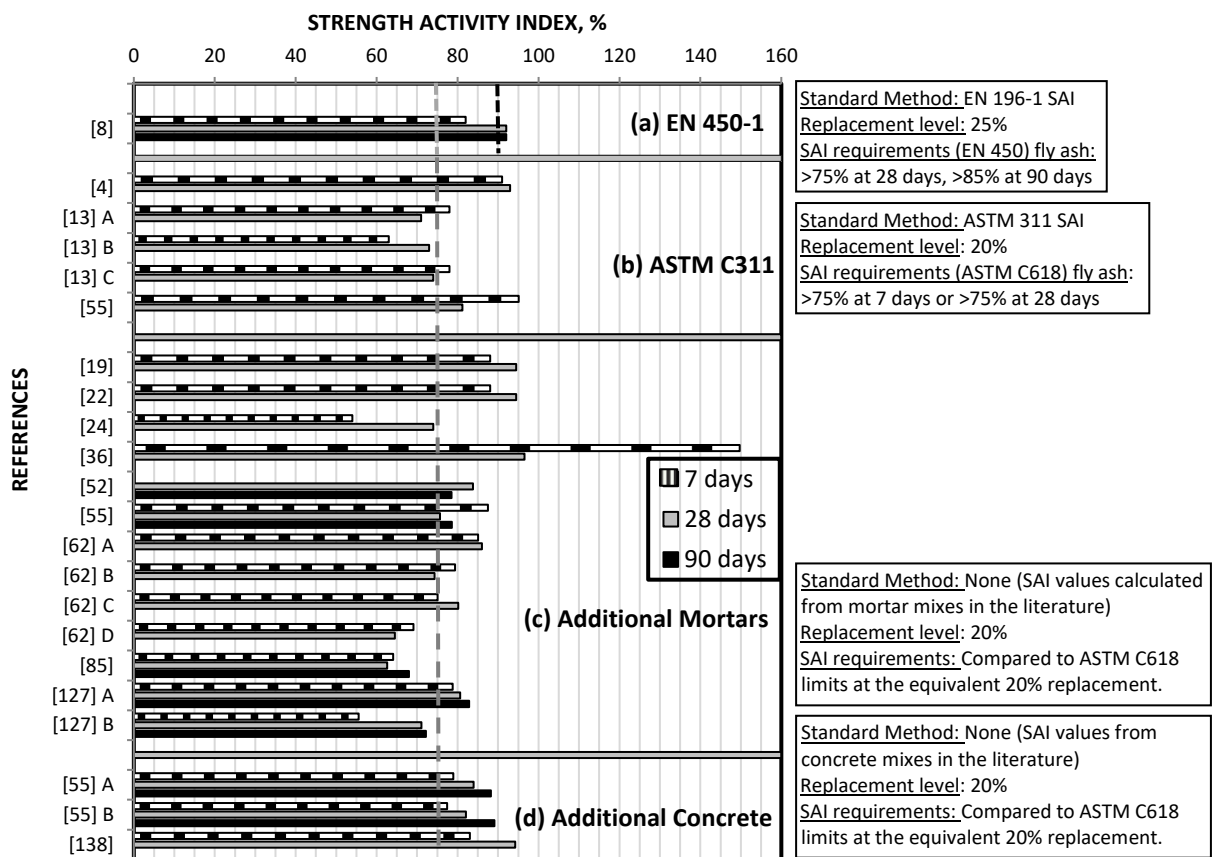
220 At higher SSA contents, up to 11%, the contents of heavy metals, sulphates and in particular
 221 phosphorus, becomes excessively high, resulting in an increase in setting times and the suppression
 222 of strength development. Treatment of SSA to extract phosphorus before use does appear to be a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

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

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

234 **4.1.2 Cement Component**

235 As a cement component, the pozzolanic activity of SSA in ground form is one of the principal factors
 236 affecting its potential for use. This property of SSA is assessed from strength activity index (SAI) tests
 237 and measuring the quantity of Ca(OH)₂ fixed. The reported results from standard SAI tests
 238 undertaken based on the procedures in EN 450 and ASTM C311, which were originally adopted for
 239 testing fly ash, are presented in Figure 4. Though not specifically in strict accordance with these
 240 standards, SAI values calculated at a 20% SSA replacement level from additional mortar and concrete
 241 mixes tested in the literature are also displayed in Figure 4.



242

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

244 In the standard tests, SSA mixes generally satisfied the respective limits outlined for fly ash of SAI

245 values greater than 75% at 7 or 28 days in ASTM C618 (2008) at the 20% replacement level and

246 greater than 75% and 85% SAI values at 28 and 90 days respectively for a 25% replacement level in

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

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

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

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

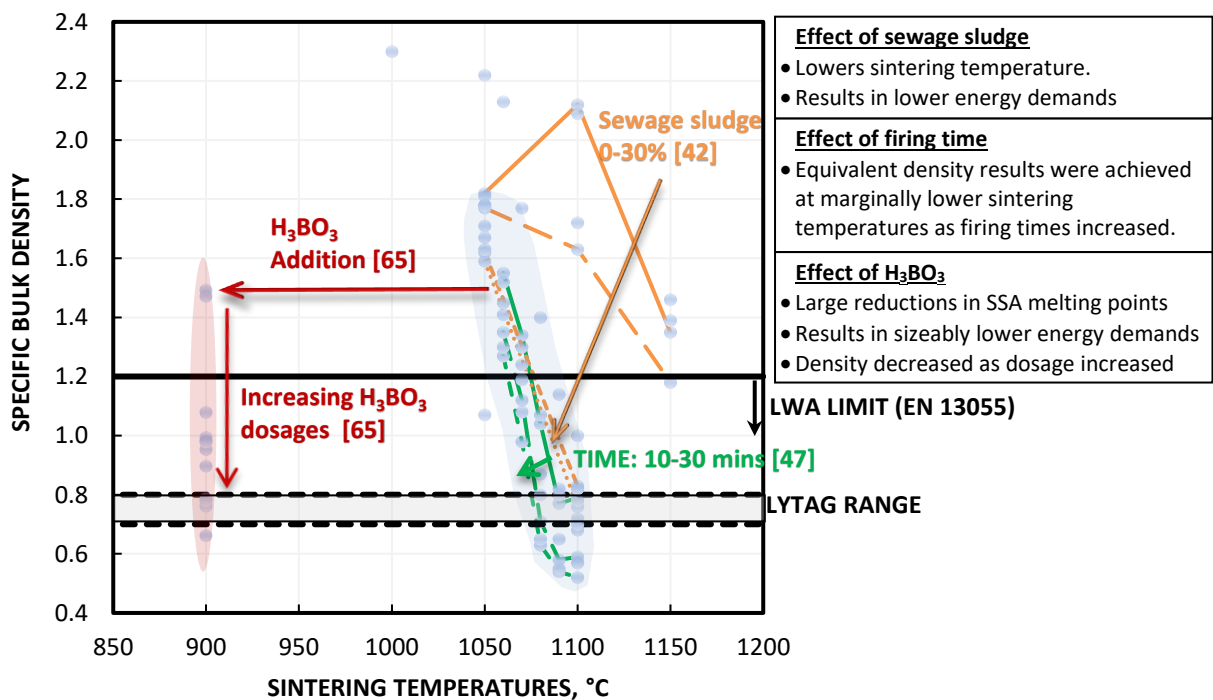
268 **4.2 Aggregate**

269 The characteristics of SSA, specifically its fineness, suggest that the material may be suitable for use
 270 in concrete as filler or fine aggregate. The reported performance of concrete using SSA in this form
 271 [7, 14, 17, 35 and 53] is covered in Section 4.3 below.

272 SSA also has good prospects as a manufactured lightweight aggregate and many attempts have been
 273 made in the literature to exploit this potential application [28, 42, 47, 48, 65, 66, 97, 109, 141-144].

274 The process typically involves pelletizing and sintering at high temperatures to produce high porosity
 275 aggregates that retain strong surface layers.

276 Mechanical and lightweight properties of manufactured SSA aggregates are strongly connected to
 277 the sintering conditions. Indeed, bulk density results after sintering at temperatures from 900 -
 278 1150°C are presented in Figure 5 [47, 42, 65 and 109]. At 1050°C, expansion processes begin to form
 279 resulting in large discontinuous irregular pores, which leads to a sharp decrease in density and
 280 strength of the manufactured aggregates.



281

282 Figure 5: Bulk density of manufactured SSA lightweight aggregate

283 At temperatures above 1070°C, SSA aggregates fall within the lightweight aggregate classification
284 limit of 1200 kg/m³ set in EN 13055-1 (2002) and are comparable to Lytag aggregate at temperatures
285 from 1080 - 1100°C. Increasing the sintering time, one example of which is highlighted [47] in Figure
286 5, also leads to a sharper decrease in bulk density.

287 The effect of additions of sewage sludge [42], boric acid (H₃BO₃) [65] and glass cullet powder [97] in
288 the production process have also been investigated. As shown in Figure 5, sewage sludge and in
289 particular H₃BO lowers the melting points of the mix, while similar behaviour is also evident with
290 glass cullet additions [97], thus the expansive processes and resultant weight losses are initiated
291 early, resulting in lower energy demand.

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

301 **4.3 Mortar and Concrete**

302 **4.3.1 Use as Aggregate**

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

305 The limited research undertaken [7 and 53] reports of large reduction in workability or large
306 increases in water contents of concrete with the use of a small proportion SSA as the sand

307 component (up to 15%) because of the alleged effect of higher than normal porosity/absorption
308 characteristics. However, it would appear that mix design has not been revised in these studies to
309 accommodate the SSA characteristics. Furthermore, were the water demand to still increase, a
310 water reducing admixture can be used to compensate for this deficiency.

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

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

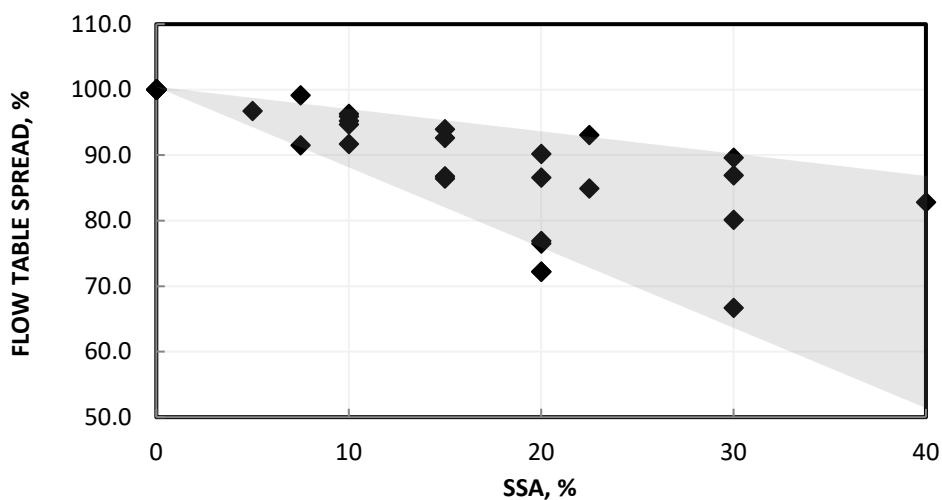
324 Capillary water absorption coefficients ranging from $0.26 - 0.9 \text{ kg/m}^2 \text{ h}^{0.5}$ have been reported for
325 concrete mixes containing up to 20% SSA [14 and 53], compared to non-SSA control values ranging
326 from $0.55 - 0.61 \text{ kg/m}^2 \text{ h}^{0.5}$. Some level of absorption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

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

334 4.3.2 Use as Binder

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

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



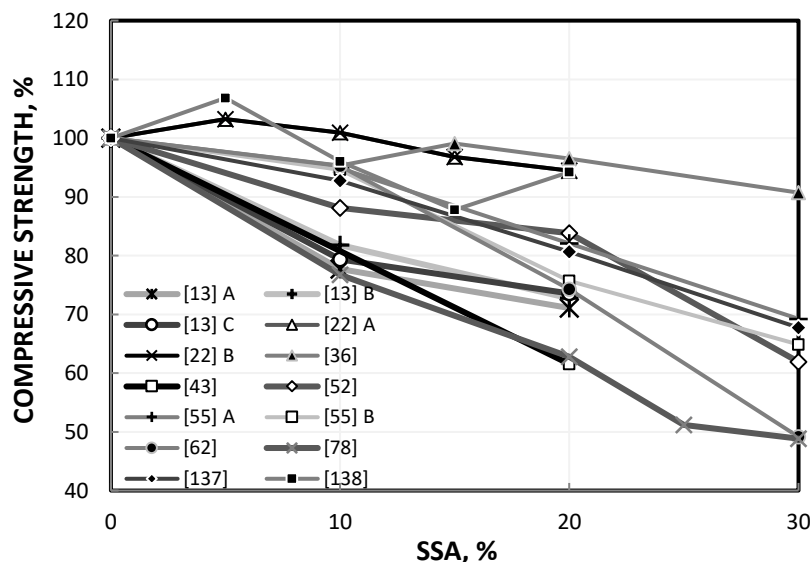
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348

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

349 Setting times lengthen with increasing SSA contents [22, 40 and 138], with an average increase of
 350 35% per 10% replacement calculated for both the initial and final setting times. Longer setting times
 351 are to be expected when using pozzolanic materials and the introduction of SSA causes no
 352 difficulties relating to the requirements of EN 197-1 (2011) for common cements, in which an initial
 353 setting time greater than 45 minutes is stated.

354 Data on the effect of SSA on compressive strength (28 days) presented in Figure 7, shows reduction
 355 with increasing SSA content, on average at the rate of 1 for 1% SSA replacement of Portland cement
 356 clinker. Lower early age strengths are typical for pozzolanic materials, though an average
 357 compressive strengths of 92% of the control at 90 days [52, 53, 55 and 137], suggests a positive
 358 strength contribution from SSA in the long term. It has also been shown that SSA can be used at
 359 lower contents and achieve strength comparable to the control using a variety of mix design
 360 adjustments, including increasing the cement content [15], using superplasticizer to lower w/c ratio
 361 of the mix [4, 13 and 43], nano-materials additions [40] and increasing the fineness of SSA [21 and
 362 81].



363
 364 Figure 7: Effect of SSA replacement level as a cement component on 28 day compressive strength
 365 Reported tensile and flexural strength data emulate the compressive strength results [5, 22, 37, 46,
 366 62, 78, 81, 137, 146 and 147], with reduction evident as SSA content is increased, though this

367 became proportionally less with age. Importantly, the data also suggests that the relationship
368 established between flexural and compressive strength in Eurocode 2 (EN 1992-1-1, 2004) is equally
369 valid for concrete mixes containing SSA.

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

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

382 Corrosion resistance has been found to improve for SSA contents up to 20%, though for higher
383 contents up to 60%, resistance lower than the control have been reported [137]. It would appear
384 that two opposing factors are at play: the positive effect of chemically binding of chlorides due to
385 the aluminium content of SSA is the overriding influence at low content, whilst, at high SSA content,
386 the continued weakening of the pore structure from increased porosity and reduced hydration leads
387 to net negative effects on durability. As such, at recommended lower contents of SSA, the impacts
388 on corrosion resistance should be positive. Increased carbonation rates have also been reported
389 [137], which is to be expected for all mixes incorporating pozzolanic materials as cement
390 component.

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

395 **4.4 Blocks**

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

399 As fine aggregate, two main findings emerged:

- 400 • Blocks produced with a 10% addition of SSA as aggregate had greater strength, higher density
401 and lower absorption properties compared to the control. Though this appears to be somewhat
402 contradictory to previous findings with SSA, the improvements have been attributed to the
403 filling effects of the fine particles of SSA [53].
- 404 • Up to 35% SSA could be included as aggregate and still satisfy a target 20 MPa strength
405 requirement. This could be increased to 40% in air entrained and water reduced concrete mixes
406 and indeed as reported in section 5. Case Studies, using blocks with this mix design, had been
407 used in a field study as erosion control structures in Long Island, USA. After 12 months of
408 monitoring, no weathering or deterioration of the blocks was evident [149].

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

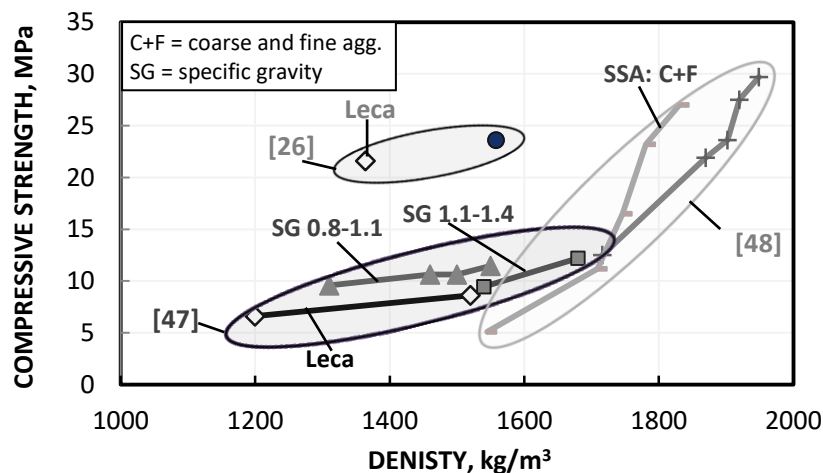
- 410 • Precast blocks containing up to 20% SSA demonstrated remarkably low degree of variability and
411 high repeatability. The dimensional stability and configuration of the SSA blocks are within the
412 allowable tolerances, the coefficient of variation of the apparent and water saturated densities

413 were very small (maximum of 0.008) and the compressive strength standard deviations for the
 414 20% SSA blocks were below the control blocks (7% compared to 10% for the control blocks) [31].

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

421 4.5 Lightweight Aggregate Concrete

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



426
 427 Figure 8: Compressive strength (28 days) and density behaviour of
 428 concrete mixes containing lightweight SSA aggregate
 429

430 The SSA lightweight aggregate concrete mixes achieved strength (28 days) suitable for structural
 431 application, reaching up to 30 MPa. Strength greater than the Leca aggregates mixtures have been

432 reached, though SSA mixes generally had higher densities, but most remained within the
433 lightweight concrete guidelines i.e. less than 1850 kg/m³.

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

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

448 **4.6 Aerated Concrete**

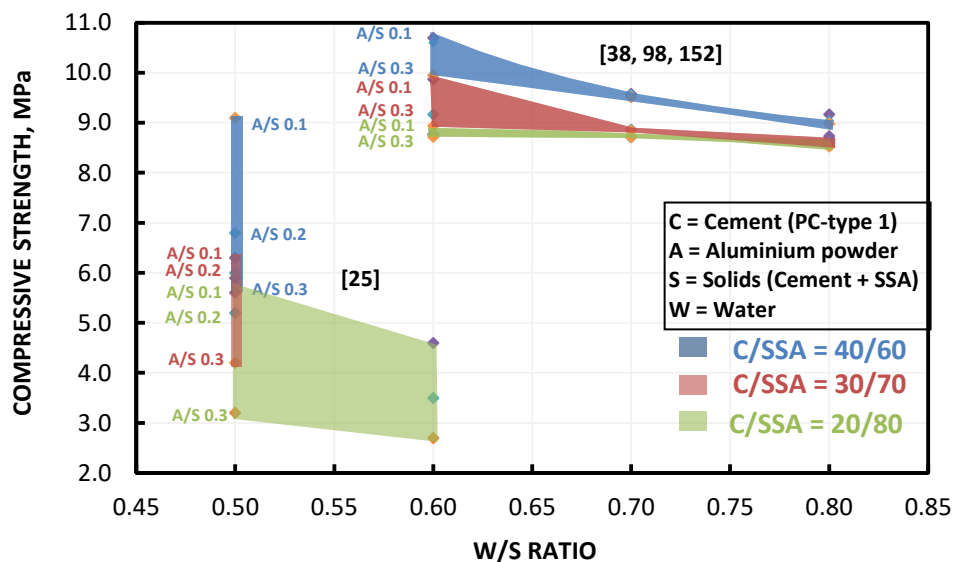
449 SSA appears suited for use in aerated concrete, as its high aluminium content and porous nature can
450 contribute to delivering the desired lightweight and thermal properties. Although of filler fineness,
451 the material has been used as replacement of cement [25, 38, 98 and 152] and PFA [153]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

454 A group of the same authors [25, 38, 98 and 152] have used SSA in bulk quantities (up to 80% by
455 weight of cement) in "lightweight foamed materials" mixes. The process of casting the cubes, de-

456 moulding, curing and cutting away any excess bulging, is symptomatic of aerated concrete
 457 production rather than foamed concrete, which typically involves the addition of premade foam to a
 458 base mix.

459 Compressive strength results (28 day) are presented in Figure 9 [25, 38, 98 and 152] for mixes with
 460 SSA contents from 60 - 80%, aluminium powder dosages from 0.1 - 0.3% and water/solids (w/s)
 461 ratios from 0.5 - 0.8, where solids represents the sum of cement and SSA. It appears that SSA
 462 content had the greatest impact on strength, though the effect of both SSA and aluminium powder
 463 is more pronounced at lower w/s ratios. It is encouraging that mixes with high SSA contents can
 464 comfortably satisfy the minimum strength limit of 1.5 N/mm² of EN 771-4 (2011) for autoclaved
 465 aerated concrete masonry units.

466 Increasing the SSA and aluminium powder contents both led to higher porosity which improved the
 467 thermal and lightweight properties of the products. Specific gravity from 0.6 – 1.0 and thermal
 468 conductivity from 0.09 – 0.24 W/mK have also been achieved. The net density of autoclaved aerated
 469 concrete is usually between 300 and 1000 kg/m³, according to EN 771-4, whilst thermal conductivity



470
 471

Figure 9: Compressive strength behaviours of SSA aerated concrete mixes

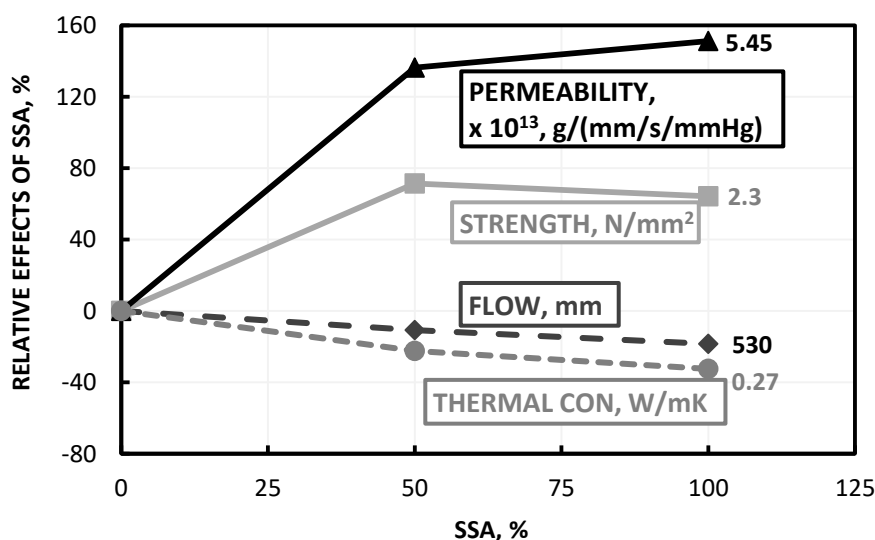
472 requirements of 0.12 - 0.15 W/mK have been reported in Taiwanese Standards [133], both of which
473 are achievable with SSA mixtures.

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

477 4.7 Foamed Concrete

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

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



488
489 Figure 10: Effects of SSA as fine aggregate on foamed concrete properties [13]

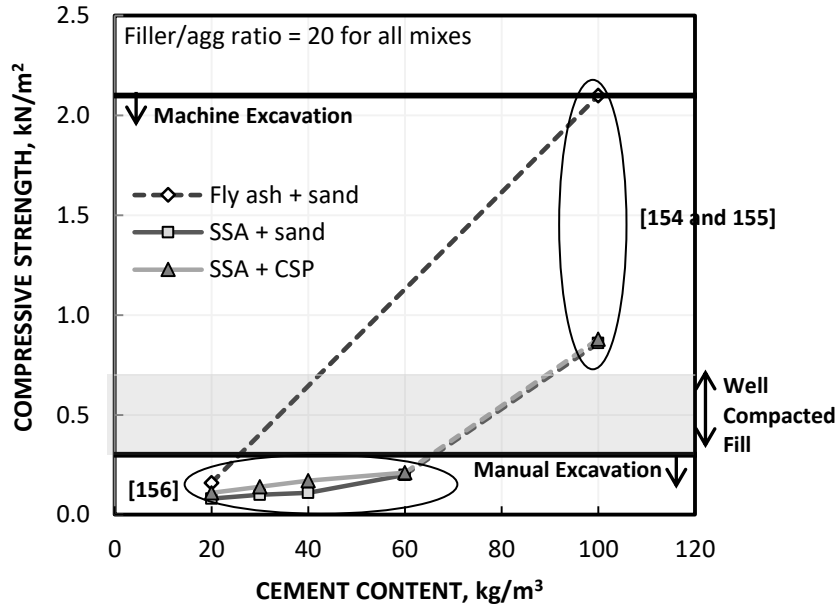
490 **4.8 Controlled Low Strength Materials (CLSM)**

491 Controlled low strength materials (CLSM) are also becoming more prevalently used as backfill
492 material. Low strength is required to facilitate future excavations, along with flowable consistence,
493 self compacting and self curing properties. The American Concrete Institute guidance report (ACI
494 229R-5) recognises Portland cement and fly ash (as filler) as the conventional materials used
495 alongside coarse and fine aggregate. Suitable nonstandard materials are permitted, though SSA is
496 not mentioned in name, as research on the material is only at the early stages.

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

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

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



511

512

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

513 **5. Case Studies**

514

The practical applications of SSA appears to be still very much in its early stages, though perhaps

515

private organisations undertaking work of this nature are reluctant to release the information

516

publically. However, the limited reported case studies are judged to be encouraging for developing

517

the use of SSA in concrete and concrete related products and are briefly described in Table 3.

518

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. Blocks: SSA as 10% replacement of coal bottom ash in medium density blocks	Strength similar to the control achieved by using superplasticizer and lowering the w/c. Increased shrinkage has been reported. 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.

519

Indeed, the reported findings are, for the most part positive, though there have been some issues

520

that can be expected when experimenting with a new product. In concrete mixes, performance

521 similar to the control have been achieved with SSA, both as fine aggregate and in ground form as
522 cement component, through modification of the mix designs, including superplasticizer addition
523 with a lower w/c ratio or increased cement contents. Encouraging performance has also been
524 achieved with SSA in the manufacture of normal weight concrete blocks, CLSM and aerated
525 concrete, though the latter application highlighted the changes in the water demands when using
526 SSA as a replacement of fly ash.

527 **6. Further Research Opportunities to Enhance SSA Use**

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

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

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

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

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

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

554 **7. Conclusions**

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

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

- 567 ii. As raw feed in cement clinker production, SSA can be used at low contents and achieve
568 performance comparable to control Portland cement clinker blends. At marginally higher
569 contents, treatment of the material to extract phosphorus appears to be a reasonable
570 option that removes inhibiting effects on strength and setting behaviour. Furthermore, the
571 phosphorus removed can also serve as a valuable resource for agricultural purposes.
- 572 iii. As fine aggregate and filler aggregate components in mortar and concrete, the effects on
573 strength performance appear to be manageable at low SSA content up to 15% and through
574 revision of the mix design to accommodate the characteristics of the material, perhaps
575 including water reducing admixtures, satisfactory workability can also be achieved.
- 576 iv. As a cementitious component, SSA satisfies the standard pozzolanic activity measures in the
577 majority of cases and in this regard is comparable to fly ash. In mortar and concrete mixes,
578 using SSA as a direct cement replacement results in lower strength and workability, though
579 at low contents, performance on par with the control can be achieved by adjusting the
580 cement content or using superplasticizer to lower the w/c ratio of the mix. Nano-materials
581 addition and increasing fineness can also further enhance strength. Regarding durability, the
582 impacts on corrosion resistance at low SSA content appears to be positive, the carbonation
583 rate increases as is expected for all mixes using pozzolanic materials and no significant
584 expansion occurs during sulphate resistance testing.
- 585 v. The porous nature of SSA makes the material a good prospect for use in a range of
586 lightweight applications, both in as-produced and ground form. A great deal of flexibility can
587 be achieved in the performance of concrete made with manufactured SSA lightweight
588 aggregate through adjustments of the sintering process and mix designs, with strengths
589 suitable for structural applications attainable, along with lightweight properties comparable
590 to commercially available Leca mixes. SSA can be used in bulk quantities in CLSM, as well as

591 in aerated and foamed concrete and can satisfy the low strength, workability, lightweight
592 properties and thermal requirements of the respective products.

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

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982 **Table captions**

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

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

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

986 **Figure captions**

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

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

990 Figure 3: Ternary plot of SiO₂, Al₂O₃ and CaO contents for SSA

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

992 Figure 5: Bulk density of manufactured SSA lightweight aggregate

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

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

- 995 Figure 8: Compressive strength (28 days) and density behaviour of concrete mixes containing
996 lightweight SSA aggregate
- 997 Figure 9: Compressive strength behaviours of SSA aerated concrete mixes
- 998 Figure 10: Effects of SSA as fine aggregate on foamed concrete properties [13]
- 999 Figure 11: Compressive strength performance of CLSMs containing SSA as filler material.