Sewage sludge ash characteristics and potential for use in bricks, tiles and glass ceramics

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Title: Sewage Sludge Ash Characteristics and Potential for Use in Bricks, Tiles and Glass Ceramics

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ABSTRACT

The characteristics of sewage sludge ash (SSA) and its use in ceramic applications pertaining to bricks, tiles and glass ceramics have been assessed using the globally published literature in the English medium. It is shown that SSA possess similar chemical characteristics to established ceramic materials and under heat treatment achieves the targeted densification, strength increases and absorption reductions. In brick and tile applications, technical requirements relating to strength, absorption and durability are achievable, with merely manageable performance reductions with SSA as a partial clay replacement. Fluxing properties of SSA facilitate lower firing temperatures during ceramics production, though reductions in mix plasticity leads to higher forming water requirements. SSA glass ceramics attained strengths in excess of natural materials such as granite and marble and displayed strong durability properties. The thermal treatment and nature of ceramic products also effectively restricted heavy metal leaching to low levels. Case studies, predominantly in bricks applications, reinforces confidence in the material with suitable technical performances achieved in practical conditions.

Key Words: Bricks, Glass Ceramics, Sewage Sludge Ash, Tiles

INTRODUCTION

Sewage sludge is a by-product of wastewater treatment. With ever reducing limits on the allowable biodegradable landfilled fraction [European Community (1999)], combined with a ban on its disposal at sea [European Community (1991)] and restrictions on its spreading on agricultural land, management of the waste has shifted towards more environmentally friendly treatment methods such as recycling and incineration.

The incineration process leads to a 90% reduction in volume, leaving behind residual sewage sludge ash (SSA), whilst the high temperatures involved in the combustion process reduce the toxic components remaining in the ash.

The ever increasing global emphasis on sustainability and with it, developing the greater use of sustainable materials, calls for the use of all the so-called waste materials as valuable resources and in this case, establishing SSA as a viable secondary construction material can contribute greatly to realising this target. Indeed, the use of SSA in ceramic products, such as bricks and tiles and glass ceramics offers great promise given the vast size of the industry, whilst the thermal processes involved in production may also have beneficial impacts on diminishing concerns regarding leaching of heavy metals in SSA.

Much research has been undertaken worldwide, studying the characteristics of SSA and its use in ceramic applications, though in its current form carried out by different authors, in different countries and with different approaches, the research remains largely fragmented and not utilised to the fullest. As such, a critical evaluation of the collective data, including technical and environmental assessment, along with the work from case studies, can be useful and timely, both to advance the safe and sustainable use of SSA and to lessen future repetitive work and squandering of resources.

THE PROJECT

A critical analysis, evaluation and repackaging of the global literature published in the English medium, is undertaken, studying the physical and chemical characteristics of SSA and its potential use in ceramics applications, pertaining to construction products such as bricks, tiles and glass ceramics.

A comprehensive search using SSA related keywords in over thirty search engines and databases yielded a total of 196 publications, produced since 1972 from 33 countries across Europe (92 publications), Asia (80), North America (14), Africa (4), South America (4) and Australia (1), with key contributions coming from Taiwan (31 publications), Japan (26), UK (24), Spain (15), German (14) and USA (13).

Due to the large volume of literature, publications providing data solely relevant to the characteristics of SSA were not cited, to avoid overwhelming the messages delivered in the text. However, the lists of these publications are provided as supplementary data.

SEWAGE SLUDGE ASH CHARACTERISTICS

Analysis of the characteristics of SSA is based on data extracted from 168 publications from 30 countries, produced since 1972, with the yearly publication breakdown presented in **Figure 1**. The level of research carried out on SSA is on the rise, with the majority of work undertaken in the last 10 years, reflecting the growing importance of incineration and recycling of secondary materials.

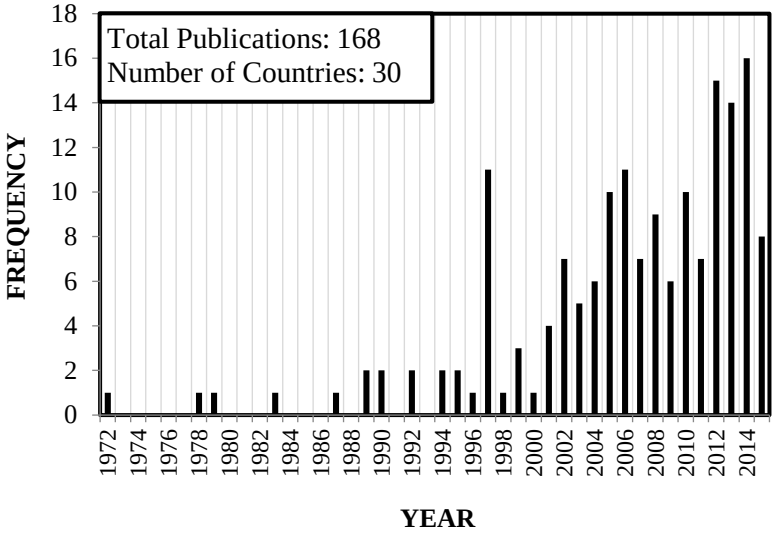

Figure 1: Yearly breakdown of the stock of literature on the characteristics of SSA

Physical Characteristics

SSA has been reported as a free-flowing, odourless material with a yellowish-brownish colour. Analysis of the fineness of SSA, along with particle size distribution curves presented in **Figure 2**, show that the material is composed predominantly of fine sand and silt size particles, suggesting natural suitability as filler material in ceramics, or as a replacement of clay after grinding. The grinding process can also help to regulate the particle size spread evident in **Figure 2**, given the precise dimensional tolerances and configuration requirements set for ceramic products such as clay masonry units.

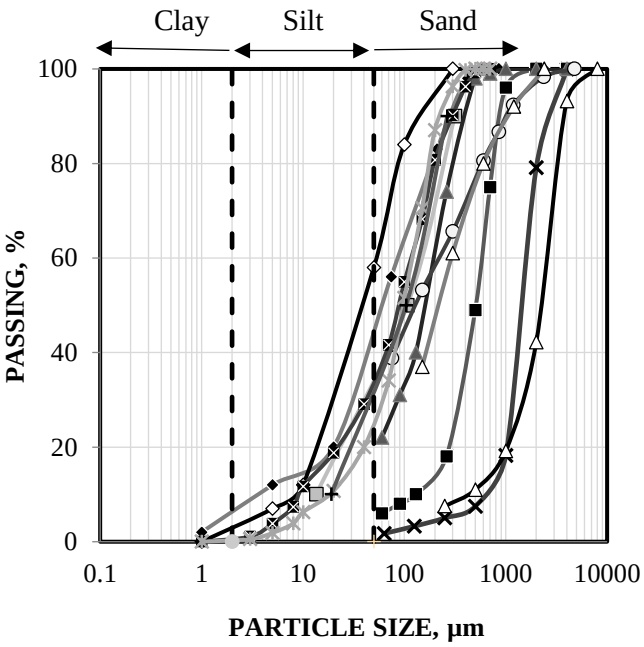

Figure 2: Particle size distribution curves reported in the literature for as-produced SSA

Specific gravity values ranging from 1.8-2.9 have been reported, though the data is skewed towards the upper end of this range due to one particularly low value [Jamshidi et al. (2012)], with average and standard deviation values of 2.6 and 0.3 respectively (45 SSA samples).

Density has been shown to increase with higher incineration temperatures, whilst the percentage of the denser heavy metal components contained in the ash is another key determining factor in the overall density.

The low ratio of bulk specific gravity (average of 0.9 for 13 samples) to particle specific gravity is indicative of a porous material. This is consistent with observations of the morphology of SSA that revealed irregularly shaped particles with rough surface textures and a porous microstructure. This porosity promotes high water absorption properties and indeed an average absorption value of 18% has been determined from the literature (8 samples), though it should be noted that two extreme values of 1.8% and 48% have been reported by Al-Sharif and Attom (2014) and Environmental & Water Technology Centre of Innovation (2012), respectively.

Chemical Characteristics

A ternary plot of the main oxides in SSA samples from the literature is presented in **Figure 3**, along with the composition of other established ceramic materials given as references. It is evident that SSA contains high contents of SiO_2 and Al_2O_3, oxides that are commonly present in ceramic materials, though the material has a higher CaO content, with an average value of 14.5%.

Fe_2O_3 is another main oxide found in SSA (average content of 11.6%) that is also commonly found in ceramic materials. This component, along with other oxides such as CaO and P_2O_5, can lead to added benefits due to fluxing properties, which can lower the melting temperature of the mixture during sintering and reduce energy costs. Besides the above similarities, the contents of P_2O_5 and SO_3, with average values of 13.7% and 3.5% determined respectively for SSA, are much greater than what is typically present in standard materials used in ceramics production.

Oxide	200 SSA Samples		
	Mean, %	St Dev, %	CV, %
SiO_2	32.8	12.5	38.2
CaO	14.5	9.0	62.1
Al_2O_3	14.0	6.6	46.7

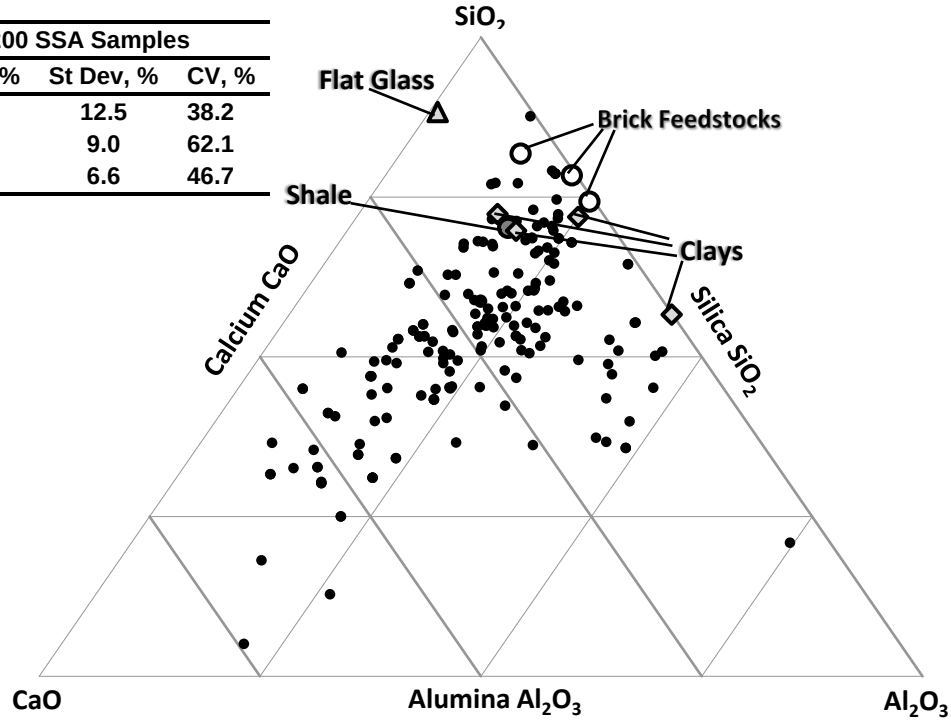

Figure 3: Analysis of the main oxides of SSA

Low amounts of organic matter have remained in SSA after incineration. An average LOI (loss on ignition) of 3.9% has been calculated based on the sourced literature (49 samples) and though irregularly high values of approximately 15% have been reported in some cases [USEPA (1972)], the organic content of SSA is generally lower than materials such as clay and shale. The additional thermal treatment involved in ceramics production should also minimize the presence of organics in the final product.

Quartz, calcite and hematite have been identified as the most abundant minerals present in SSA, whilst glass contents ranged from 35-75%. Many other iron oxides, iron phosphates, calcium phosphates, aluminosilicates and aluminium phosphates have been reported to a lesser extent, depending on factors such as the raw sludge composition, additives used during processing or incineration and the incineration temperature. SSA possesses some similarities to brickwork feedstocks and clays, which typically contain minerals such as quartz, calcite, hematite, kaolinite, feldspar and mica. The interaction and mineralogical evolution of SSA with these materials under firing will have a key impact on the properties of the resultant products.

An analysis of the element composition, according to the reported data is presented in **Table 1**, including both toxic and non-toxic components. The variability evident from the coefficient of variation results is quite striking and can be attributed for the most part to differences in wastewater treatments systems and the incineration conditions around the world.

If current EU landfill leaching classification limits [European Community (2003)] were applied, SSA would not meet the classification as an inert material due to the leached contents of heavy metals such as Cd, Cr, Cu, Ni, Pb and Zn. However, the high temperatures involved in the firing process and make-up of the resultant ceramic products can significantly downgrade the risks associated with leaching of harmful components from SSA, while at the same time the material is serving as a valuable construction material and also reducing landfilling demands, thus making this particular use very appealing.

The presence of active soluble salts in raw materials, in general, is a recognised concern in ceramics production that can negatively affect the manufacturing process, product aesthetics and durability.-In this regard, maximum limits on the Na^+, K^+ and Mg^{2+} soluble salt contents are set in EN 771-1 for the produced clay masonry units. Though not frequently covered in the literature, two publications have reported on the content of soluble salts in SSA as varying from 0.15 - 1.52%. The effects of these components in SSA on the resultant ceramic products is considered in the next Section on ceramics applications. However, if required, chemical additives are available to restrict the movements of these components [Anderson and Skerratt (2003)], though the potential variability in the soluble salts contents and the associated variability in the chemical additives required would have to be considered.

Table 1: Element composition of SSA

ELEMENT	SAMPLE NUMBERS	MEAN mg/kg	S.D. mg/kg	CV %
TOXIC				
Fe	33	75664	54231	72
Al	31	45771	27026	59
Zn	88	2988	3506	117
Cu	89	1826	3078	169
Ba	11	1909	724	38
Cr	77	585	1069	183
Sr	8	399	150	38
Pb	86	344	445	129
Ni	69	228	371	163
V	15	147	181	123
Co	15	150	180	119
Se	9	8	12	162
Sb	10	32	25	77
As	36	26	43	164
Cd	70	18	61	343
Hg	37	2	3	148
NON-TOXIC				
Si	13	108667	54575	50
P	31	63084	37316	59
Ca	26	67176	35165	52
Na	20	11055	20125	182
Mg	22	13038	6053	46
K	19	8663	6327	73
Ti	11	2454	3196	130
Mn	30	1149	753	66
Zr	10	377	251	67
Sn	12	128	153	119
Ag	10	216	198	92
Cl	28	1526	3149	206
Mo	32	29	31	107

USE IN CERAMIC APPLICATIONS

Characterisation as a Ceramic Material

Although much work has been done on the use of SSA in specific applications such as bricks, tiles and glass ceramics, preliminary information on the generic response of the material to the ceramics production process is limited [Anderson and Skerratt (2003), Cheeseman et al. (2003), Lin et al. (2006b), Merino et al. (2005), Merino et al. (2007) and Okufuji (1990)].

As a ceramic material, a basic understanding of the behaviour of SSA during the heating/cooling process is required. In addition, properties such as dimensional stability, density, strength, thermal properties, water absorption, and durability are of importance. From an initial thermal analysis, softening and melting point temperatures for SSA have

ranged from 1210-1280°C and 1250-1300°C respectively [Merino et al. (2005) and Okufuji (1990)]. Apparent density results are presented in **Figure 4 (a)** for SSA specimens produced at various maximum heating temperatures and in addition the effects of heating dwell times, compaction pressures and preparation treatments that have varied in these studies, are also portrayed.

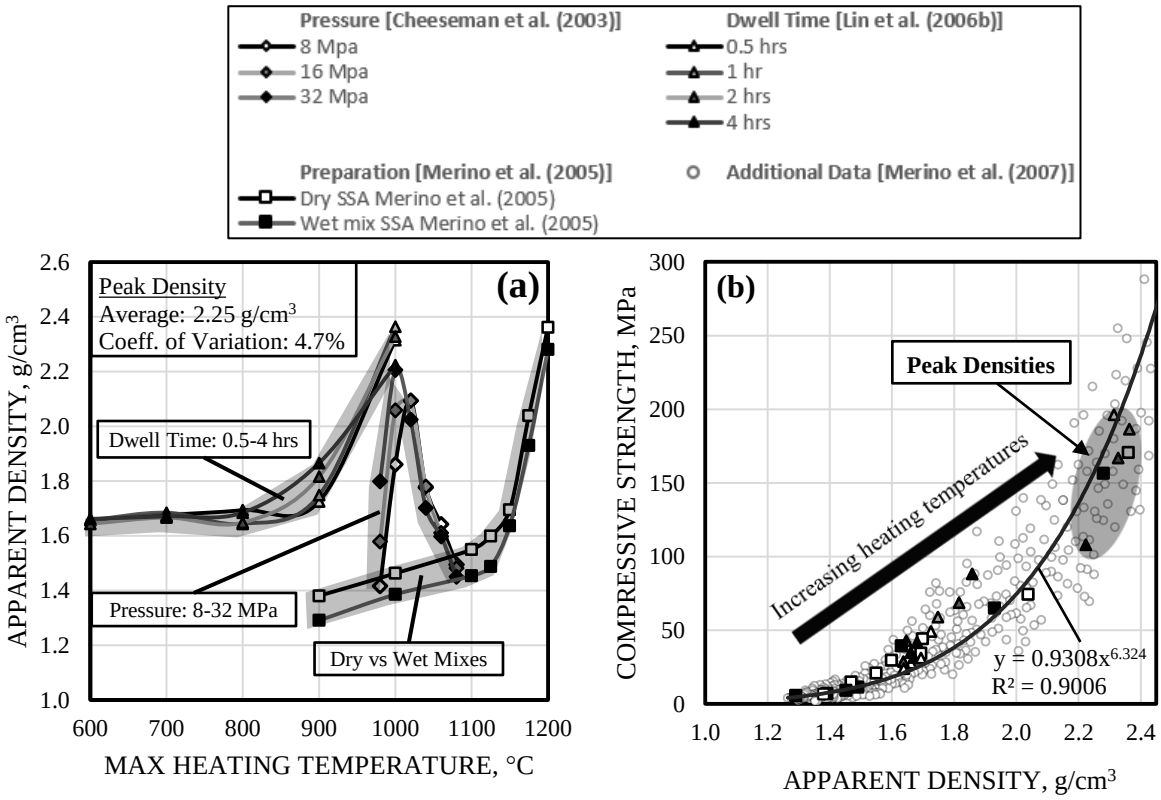

Figure 4: Relationship between (a) apparent density and maximum heating temperature and (b) apparent density and compressive strength after thermal treatment.

Figure 4 (a) shows that with densification of the material during heating, involving shrinkage of pore spaces, identified by the SEM analysis of Lin et al. (2006b), SSA attains a maximum average density of about 2.25 kg/m^3 at 1000-1200^{0}C with coefficient of variation under 5%. It appears that variations in heating dwell time, compaction pressure and preparation methods had little effect on the peak density. As previously stated in the characteristics section, variation in the temperature required for the SSA to attain maximum density is known to be influenced by the fluxing properties of oxides such Fe_2O_3, CaO and P_2O_5. Beyond the optimum firing temperature (i.e. point of peak density), a bloating phenomenon is instigated leading to the creation of large isolated pores and therefore a steep decline in density, as is evident in **Figure 4 (a)**.

Strength increases are related to density by a power relationship as shown by the trendline in **Figure 4 (b)**. The correlation seems to remain consistent despite variations in firing temperature and time, compaction pressure and preparation methods. As the maximum densities achieved for the range of test setups were all relatively similar, a reasonable assessment of the maximum strengths attainable with SSA can be gained from **Figure 4 (a) and (b)** combined.

Control of the water absorption properties is important with SSA, given the porous and absorptive nature of unprocessed material and can be particularly crucial in certain situations such as with externally exposed ceramic units. Encouragingly, the water absorption properties have been shown to be inversely related to density and compressive strength and reduce drastically from 30% to less than 1% [Cheeseman et al. (2003), Lin et al. (2006b) and Merino et al. (2007)], as density increases to a maximum. Absorption rises at temperatures past optimum firing conditions due to the bloating effect.

There appears to be a lack of research on the durability of SSA as a ceramic material per se, though its performance in this regard is catered to with the specific products such as bricks, tiles and glass ceramics.

In ceramics production, a level of consistency in the raw materials is a clear requirement, particularly given the importance of chemical composition on the optimum firing temperature (**Figure 4 (a)**). For fired SSA samples taken over a six week period from the same incineration plant, tensile strengths results ranged from 6-15 MPa [Anderson and Skerratt (2003)], though the variability has been attributed to differences in the particle size distributions and not chemical compositions, as all samples demonstrated comparable fusion/melting behaviour. This is helpful as the particle size distribution of SSA can be regulated with sieving. In addition, when SSA is used in small proportions, these inconsistencies would likely not significantly affect the overall performance.

Of additional interest, the inclusion of various clays and glass alongside SSA [Merino et al. (2007)], provides an idea of the behaviour expected with SSA as a partial component in bricks, tiles or glass. Montmorillonite and illite clays led to improvements in density and compressive strength, though this was not the case with kaolin clay due to its refractory properties. The fluxing properties of powdered flat glass lowered the temperature required for densification to occur and as such, can be useful for reducing energy requirements.

Bricks

Bricks offer great promise as an outlet for SSA use, with approximately 1300 billion units produced worldwide per annum [Clean Air Task Force (2010)]. The available experimental data on the effects of SSA on the brick production [Anderson (1999), Anderson (2002), Lin and Weng (2001), Luo and Lin (2003), Tay (1987) and Trauner (1993)] shows that:

- SSA lowers the plasticity of the mix, though the associated decrease in the bonding ability can be overcome using additional tempering water and the effects on extrusion behaviour are not significant at low SSA contents.

- The fluxing properties of calcium, iron, phosphorus and potassium in SSA benefit the fusion behaviour, thus facilitating lower firing temperatures.

Table 2 is presented with the aim of evaluating the performance of SSA bricks specifically relative to the standard UK and USA specifications, covering BS EN 771-1 and Publicly Available Specification PAS 70 (UK) and ASTM C62-13a and ASTM C216-15 (building and facing bricks in the USA).

<u>Appearance:</u> No adverse effects on the aesthetics of the bricks have been reported, with one exception [Anderson (2002)], where “drier scum” was visible due to the soluble salts in SSA.

This is a recognised problem in general with ceramic raw materials and can be overcome using chemical additives to fix the salts.

Table 2: Overview of the UK and USA bricks performance specifications

UK SPECIFICATIONS	USA SPECIFICATIONS
Appearance	
PAS-70 - guide on appearance including colour consistency, cracks and damage	ASTM C216-15 - limits on chips, cracks, imperfections, broken bricks, colour, efflorescence
Compressive strength	
BS EN 771-1 - No minimum strength. Category I - < 5% of units below declared strength, otherwise Category II. UK National Annex Engineering bricks - Class A > 125 N/mm^2, Class B > 75 N/mm^2.	ASTM C216-15/C62-13a - Min strength: Average - 20.7 (SW), 17.2 (MW) and 10.3 (NW) MPa, Individual units - 17.2 (SW), 15.2 (MW) and 8.6 (NW) MPa.
Freeze thaw	
BS EN 771-1 - Declare resistance category: F0 - passive exposure, F1 - moderate exposure, F2 - severe exposure	ASTM C216-15/C62-13a - Freeze thaw test - SW - no unit has weight loss > 0.5% and no unit develops a crack of length in excess of the units least dimension
Soluble salts	
BS EN 771-1 - Categories: S0 (completed protected) no limits. S1 (normal exposure) Na + K < 0.17%, Mg < 0.08%. S2 (prolonged saturation) Na + K < 0.06%, Mg < 0.03%.	No requirements
Water absorption	
BS EN 771-1 - Requires water absorption to be declared. In UK National Annex - Engineering brick class A/DPC1 < 4.5%, class B/DPC2 < 7.0% (5hrs boiling test).	ASTM C216-15/C62-13a - Limits (5hrs boiling) - Average 17% (SW), 22% (MW), no limit (NW). Individual - 20% (SW), 25% (MW), no limit (NW).

Compressive Strength: SSA bricks can be produced to comply with ASTM C216-15/C62-13a and BS EN 771-1 for strength for specific grades, suggesting that the reductions with SSA contents can be manageable (**Figure 5**) and that the sensitivity of strength development to firing temperature, as evident from the results of Trauner (1993), is of greater influence than SSA use.

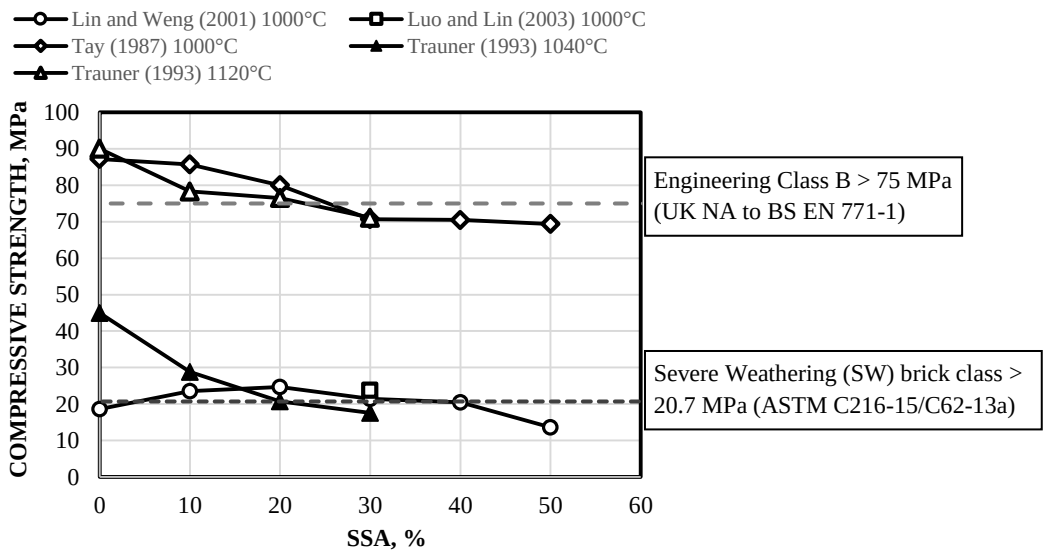

Figure 5: Brick compressive strength with SSA replacement level

Freeze Thaw: The results of Trauner (1993) show that the ASTM C216-15/C62-13a limit for severe weathering class bricks of 0.5% weight loss in freeze-thaw testing can be achieved with bricks manufactured using up to 30% SSA. The weight loss behaviour appears to mimic that of water absorption.

Soluble Salts: Although discussed in terms of the impacts on aesthetics, the soluble salts contents in SSA bricks and their potential effects on brick durability have not been measured.

Water Absorption: Whilst the effect of SSA, shown in **Figure 6**, appears to be somewhat inconsistent, variability in absorption for the control bricks, from 0.03 - 14%, again suggests a greater dependence on pore structure development during firing rather than SSA use as can be seen from the results of Trauner (1993) for firing temperatures of 1040°C and 1120°C. In relation to the performance set out in the Standards, the 5 hour boiling water test data [Lin and Weng (2001) and Tay (1987)] suggest that SSA bricks can satisfy the limits (< 17% for severe weathering) for building and facing bricks (ASTM C216-15/C62-13a). For the more stringent engineering class and damp proof course (DPC) bricks (< 7% absorption), SSA is perhaps more suited for use at low contents.

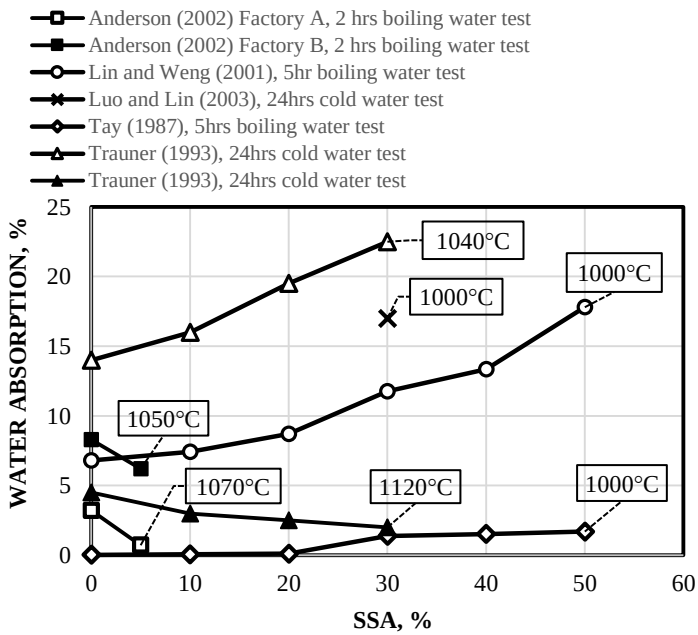

Figure 6: Brick water absorption performance with SSA replacement

Although drying shrinkage is not referred to in the UK or USA Standards, the data show that SSA benefitted the quality of the bricks in this regard, due to its lower swellability and plasticity compared to clay.

From an economic standpoint, though the value of brick making materials is quite low, with landfilling costs rising, the prospects for SSA use in bricks can only improve. It is suggested that the costs can be further reduced by situating the incineration plants and brick making facilities closer. The fluxing properties of SSA may also lead to energy savings in the production process, though additional tempering water and anti-scum agents may be required. As a sign of the interest in SSA, a number of additional publications without available experimental data, have discussed SSA use, such as: Donatello and Cheeseman (2013), Johnson et al. (2014), Kadir and Mohajerani (2011), Smol et al. (2015), Tay and Show

(1992), Vouk et al. (2015) and Wienerberger (2012). Case studies in this area are also dealt with in Section 6.

Tiles

SSA use in tiles, both glazed and unglazed, manufactured using pressuring procedures and focused as a clay replacement, has been predominantly examined in the Asian countries and evaluated in line with Chinese Standards [CNS (1999)], with no major production problems arising due to SSA [Chen and Lin (2009), Dayalan and Beulah (2014), Kaneko et al. (1992), Lin et al. (2005a), Lin et al. (2007b), Lin et al. (2008) and Okufuji (1990)]. Whilst unglazed tiles at times exceeded the 16% water absorption limit of CNS (1999), Figure 7(a), taking clay tiles as a zero baseline (Figure 7 (b)) with the exception of Lin et al. (2005a), showed that SSA had only minor effect in this respect, particularly at low SSA contents. Glazing has been found to reduce absorption, at a rate that was similar for both control and SSA tiles.

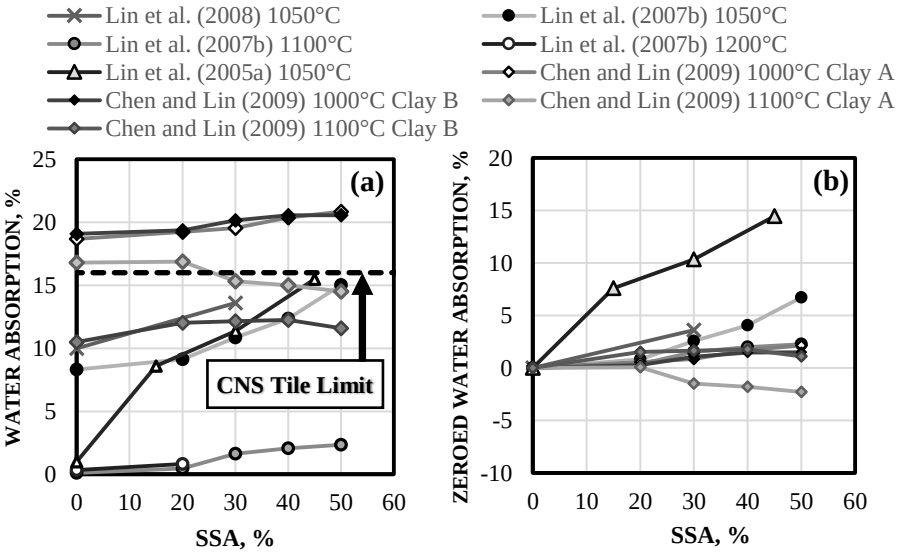

Figure 7: (a) Tile water absorption performance with SSA replacement and (b) zeroed tile water absorption displaying the isolated effects of SSA

Despite bending strength reductions, at an average rate of 0.5% per 1% SSA, all products with up to 40% SSA satisfied wall and floor tile earthenware requirements for this of 5.9 and 9.8 MPa [CNS (1999)] respectively [Chen and Lin (2009), Lin et al. (2005a), Lin et al. (2007b) and Lin et al. (2008)]. Nano-SiO_2 additions (tested up to 3%) as expected improved strength, but at greater rates with SSA, particularly at higher contents (30-50% SSA), though became ineffective at temperatures exceeding 1150°C. Glazing has been shown to further improve strength with SSA use (Lin et al, 2008), though this remains to be confirmed (Lin et al. (2005a).

All tiles (up to 50% SSA) fulfilled the CNS (1999) abrasion limit of 0.1g, despite drops in resistance with SSA [Chen and Lin (2009), Lin et al. (2005a), Lin et al. (2007b) and Lin et al. (2008)]. Glazing greatly improved abrasion (optimal glaze contents of 0.03-0.1%) and more effectively for SSA tiles compared to controls. Nano-SiO_2 additives enhanced abrasion properties at a comparable rate at all SSA contents, though only effectively at temperatures from 1050-1100°C.

SSA had no significant effect on acid-alkali or ageing resistance tests, although 0.1 g/cm^2 glaze has been needed for both control and SSA tiles for categorisation as "good" in both aspects [Lin et al. (2005a) and Lin et al. (2008)]. Due to fluxing properties, red glaze colorant (Fe_2O_3), has been most beneficial to durability, whilst purple glaze (MnO_2) has been least effective.

SSA did not significantly affect firing shrinkage of tiles. In addition, weight loss on ignition (WLOI) reduced with SSA, as the organic matter had already been burnt off during sewage sludge incineration.

Glass Ceramics

SSA use in glass ceramics requires it to be part of the process of combining melting with controlled crystallization, achieving the sealing, low porosity and fabrication advantages of glass, together with the strength and resistance properties of ceramics [Donatello and Cheeseman (2013), Endo et al. (1997), Hnat et al. (1999), Isa (2011), Park et al. (2003), Rawlings et al. (2006), Smol et al. (2015), Suzuki et al. (1997), Wystalska et al. (2013), Yoon and Yun (2011), Zhang et al. (2013) and Zhang et al. (2015)]. **Table 3**, which presents the mix details, shows that CaO has been commonly used as a conditioning additive to achieve anorthite and diopside crystalline phases known for high strength. Silica sand, soda ash and dolomite have also been incorporated at times, whilst in one case [Yoon and Yun (2011)] SSA was mixed directly with waste glass without melting.

Table 3: Mix details, heat treatment and performances of SSA glass ceramics

REFERENCE	MIX	HEATING	CS, MPA	BS, MPa	HARDNESS	TEC, 10^{-7}/°C	DENSITY, g/cm^3	WA, %	AR, %
Endo et al. (1997)	SSA+CaO	T_M 1490°C. T_C 1000-1100°C	164	n/a	n/a	67	n/a	0	0.1
Park et al. (2003)	SSA+CaO	T_M 1500°C. T_C 1050°C 2h, 1150°C, 3h	n/a	75-92	5860-6230 MPa (V)	74-83	2.87-2.93	0	< 2
Suzuki et al. (1997)	SSA+CaO+Dol +SiO_2+SA	T_M 1400°C. T_C 1000-1200°C, 1-8h	n/a	n/a	5-6 (M)	67	3	n/a	0.1
Yoon and Yun (2011)	SSA+waste glass	No melting. T_C 850-1050°C, 1h	210-270	119-156	4790-5560 MPa (V)	n/a	2.32-2.69	n/a	0.13-0.14
Wystalska et al. (2013)	SSA, SSA+Dol	T_M ? T_C 871, 986, 1150°C, 1h	n/a	n/a	6.5 (M)	n/a	n/a	n/a	n/a
Zhang et al. (2013)	SSA+CaO	T_M 1500°C. T_C 977°C, 1-3h	n/a	n/a	n/a	n/a	2.19-2.30	1.55-2.30	n/a
Zhang et al. (2015)	SSA+SiO_2 +CaO	T_M 1500°C. T_C 870, 945, 1065°C for 1- 3h	167-247	77-118	n/a	n/a	2.37-2.88	0.42-1.02	n/a
NATURAL MATERIALS									
Marble	-	-	118	6-22	3-4	80	2.6-2.8	0.2	2.5, 10.3
Granite	-	-	130	6-30	5-6 (M), 5500 MPa (V)	50-150	2.7	0.35	1

T_M = melting temperature, T_C = crystallization temperature, Dol = dolomite, SA = soda ash, CS = compressive strength, BS = bending strength, TEC = thermal expansion coefficient, WA = water absorption, AR = acid resistance, V = Vickers hardness, M = Mohs hardness.

Glass melts have been produced at approximately 1500°C, though this dropped to 1400°C in the study undertaken by Suzuki et al, (1997) using four other constituents alongside SSA. During subsequent heating, nucleation occurred at 760-800°C (optimal duration of 1 hour), with iron sulphide colloids forming as nucleating agents. Optimal crystallization occurred at

temperatures from 1000-1150°C, forming anorthite, diopside and at times wollastonite crystals, resulting in high strengths.

The resultant glass ceramic properties, also presented in **Table 3**, show that SSA products achieved compression and bending strengths well in excess of typical marble and granite values. Hardness values were within the range expected for glass (5-7 Mohs) and were comparable or out-performed the reference natural materials. Under optimal thermal conditions, densities similar to marble and granite have been achieved. The products showed no excessive susceptibility to thermal expansion or acid attack, whilst low water absorption values have also been reported.

The colour of SSA glass ceramics ranged from dark graphite to brown depending on crystallization phases and with polishing, a beautiful high quality marble-like look has been achieved [Suzuki et al (1997)].

ENVIRONMENTAL ASSESSMENT

Though the data available on brick kiln emissions is quite limited, the fact that SSA comes from an already regulated incineration treatment somewhat eases this environmental concern. In a brick manufacturing trial incorporating 5% SSA, emissions monitored over 2 days did not exceed limits specified by the Environmental Protection Act (1990) [Anderson et al. (2002)].

Heavy metal leaching results for SSA itself and in ceramic products, presented in **Table 4**, have been determined from toxicity characteristics leaching procedure (TCLP) tests, though this method is intended to determine if a waste is hazardous, based on the EPA regulatory limits. With no leaching limits given for ceramic materials, Japanese environmental quality standards for soil [Ministry of the Environment (1991)] and EU drinking water limits [European Community (1998)] have also been included in **Table 4** as indicators of performance.

Table 4 shows that:

- Leaching from SSA itself was below the hazardous classification limits, though exceeded the soil and drinking water limits in most cases.

- Sintering led to some reductions in the leaching, though cadmium concentrations remained above the soil and drinking water limits.

- Of added interest, acid neutralisation tests on sintered SSA, revealed increased susceptibility to leaching under strongly acidic conditions (pH of 3) [Cheeseman et al. (2003)].

- The leaching of tiles and glass ceramics with SSA reduced dramatically compared to the untreated material and with the cautionary exception of nickel, fell below the drinking water limits.

Thus, it would appear that the heat treatment involved and nature of ceramic products appears to make the safe use of SSA potentially viable.

Table 4: Leachability of SSA ceramic products (Note: Underline - exceeds EU drinking water parameters, bold - exceeds Japanese soil quality regulations)

TEST PRODUCTS AND REFERENCES	HEAVY METAL LEACHABILITY, mg/L					
SSA	Cd	Cr	Cu	Ni	Pb	Zn
Lin et al. (2005a)	**0.03**	**0.06**	8.24	1.97	**0.37**	8.14
Lin et al. (2006b)	**0.03**	<0.014	0.51	-	<0.016	7.04
Zhang et al. (2015)	-	**1.36**	4.64	1.22	**2.43**	3.16
Sintered SSA						
Lin et al. (2006b)						
600°C, 2hrs	**0.03**	<0.014	0.4	-	<0.016	5.49
800°C, 2hrs	**0.02**	<0.014	0.4	-	<0.016	4.55
1000°C, 2hrs	**0.02**	<0.014	0.57	-	<0.016	2.82
Tiles						
Lin et al. (2005a)						
45% SSA + 55% clay, 1050°C	0.002	0.039	0.991	0.123	-	0.196
Glass Ceramics						
Zhang et al. (2015)						
SSA + CaO/SiO_2 additives, 945°C,	-	0.01	0.11	0.06	0.01	1.14
SSA + CaO/SiO_2 additives, 1065°C,	-	0.02	0.08	0.05	0.01	1.02
Endo et al. (1997)*						
SSA + CaO additive, 1100°C (A)	<0.01	0.002	-	-	<0.01	-
SSA + CaO additive, 1100°C (B)	<0.01	<0.05	-	-	<0.01	-
Limits						
EPA hazardous regulatory limits	1	5	15	15	5	-
Japanese Soil Quality Regulations	0.01	0.05	-	-	0.01	-
EU Drinking Water Parameters	0.005	0.05	2	0.02	0.01	-

* Leaching method not specified.

CASE STUDIES

Case studies on SSA in ceramics have focused mainly on brick applications and the details of work done and the findings described in **Table 5.** The material has been used in quite a variety of ways in these projects, including as a filler component in place of sand together with clay, or as the sole raw material in brickmaking.

Table 5 indicates that effective practical use of SSA in ceramics has been achieved, with the products attaining satisfactory strength, absorption and durability properties and indeed, as a filler component, the material appears to be an upgrade over sand. Issues such as scumming, have been overcome by limiting the water absorption levels [Okuno and Takahasi (1997)], whilst increased forming water requirements have been counteracted by combining SSA with another waste material (water treatment residue) that on its own had a problematically high water content [Anderson et al. (2002)].

Table 5: Description of work undertaken and findings on ceramics case studies with SSA

REFERENCE	WORK UNDERTAKEN	FINDINGS
Anderson et al. (2002)	UK. 200000 experimental bricks with SSA, WTR and CY from 0-10%, with clay.	After experimentation with mix designs, a final mix of 5% of each of SSA, WTR and CY achieved satisfactory production speed, mechanical, durability and aesthetic properties.
Anderson et al. (1996)	UK. Trial bricks with 8% SSA replacing sand based on a commercially used feedstock.	SSA is an upgrade over sand, with bricks achieving greater mechanical performance, no adverse effects on colour. Increased tempering water and staining were flagged as future possible issues.
DEFRA (2007)	UK. General overview of the use of wastes in bricks in the UK	States that SSA is in use in 1 plant in UK at the time, though no figures provided. Fluxing agent, filler and colourant are listed as possible functions of SSA in brickmaking
Mödinger (2002)	Italy. Industrial production was commencing with ceramic matrix composites using SSA.	Results not provided, yet it is reported that the reduced plasticity associated with SSA, would limit its use to lower contents.
Okuno and Takahashi (1997)	Japan. Bricks made 100% SSA, operating in 8 plants, 900000 bricks per year.	Bricks achieved satisfactory strengths and aesthetics. Restricting absorption below 5% avoided problems related to moss growth, iced surface and scumming. Chemical coating enhanced long term durability.
Okuno et al. (2004)	Japan. Environmental and economic LCA of the previous project with 100% SSA bricks	Brickmaking LCA: Environmental – 0.076 kg CO_2 / kg dewatered sludge used. Energy cost - 4.27¥ / kg dewatered sludge. Energy costs calculated exceeded the product sellable prices (2.2¥/kg dewatered sludge).
Petavratzi (2007)	UK. Pilot scale brick production with 2.5 and 5% SSA.	SSA demonstrated suitability as a filler or sand replacement. It was indicated that greater amounts of tempering water would be required with SSA. Scumming was present, though at an acceptable level.
Petavratzi and Barton (2007b)	UK. Industry study on brick manufacture, including the use of waste materials.	Similarly to the DEFRA report, states that SSA is in use in 1 plant in the UK, though further details are not provided.
Satoshi and Hiroki (1993)	Japan. Patent to produce water permeable block brick from SSA	Patent covers the production process, no details are given on the performance of the resultant brick products.
Smith (2014)	UK. Reviews the use of non-primary clay materials in UK brickmaking	564 and 470 t of SSA used in brickmaking in 2005 and 2006 respectively, 0 usage from 2007-2010. Outlines many positives of using secondary materials including reduced energy usage and carbon footprint.

WTR – water treatment residue, CY – carpet yarn

Reservations about the environmental and economic competitiveness have been raised based on high CO_2 production and past energy costs in excess of the market value of bricks made from 100% SSA [Okuno et al. (2004)]. However, these economic conditions are subject to change, driven by the increasing importance of sustainability and continuous improvement of the thermal technologies to be more suited to these secondary materials. In addition, perhaps the gentle incorporation of SSA at low contents can be a more economically viable option rather than as the entire feedstock.

The performance-based approach now adopted in the EU standards also offers greater opportunity for the use of materials such as SSA, rather than past material-based specifications. Other important benefits that can encourage SSA use such as reduced landfill and extraction costs and conserving natural resources, are well known.

CONCLUSIONS

Analysis of the data suggests that SSA use in ceramics pertaining to bricks, tiles and glass ceramics is feasible, with potential for wide application. The specific findings are given as follows:

i. The fineness of SSA suggests natural suitability as filler material. Its irregularly shaped rough textured particles and porous microstructure leads to high absorption properties. SSA shares the same main oxides (SiO_2, Al_2O_3 and CaO) and minerals (quartz and calcite), that are commonly found in ceramic materials, whilst the fluxing properties of CaO, Fe_2O_3 and P_2O_5 can benefit fusion during heating. Heavy metals in SSA give rise to leaching concerns that must be controlled, whilst soluble salts present can potentially affect product aesthetics. SSA achieves optimal densification and associated high strengths and low absorption properties during firing at 1000-1200°C.

ii. In brick production, the fluxing properties of SSA facilitates lower firing temperatures, though additional forming water has been needed due to decreased plasticity. Strength and absorption requirements for building and facing bricks, have been satisfied with up to 50% SSA. Dried scum has been visible on occasion, but can be managed with anti-scum agents. Bricks with up to 30% SSA satisfied the most severe freeze-thaw resistance limits.

iii. No production problems arose with up to 50% SSA in both unglazed and glazed tiles. Despite drops in strength, products with up to 40% SSA satisfied wall and floor tile earthenware requirements, whilst effects on absorption appeared to be minor. Abrasion resistance requirements were satisfied for all SSA tiles, whilst acid-alkali and ageing resistance and firing shrinkage properties were not significantly affected. Heavy metal leaching is controlled effectively in tiles, falling predominantly below EU drinking water limits.

iv. Melting at 1500°C, nucleation at 760-800°C and crystallization at 1000-1150°C has resulted in optimal glass ceramics performances with SSA. Strengths exceeded typical values for granite and marble. SSA products displayed suitable durability and exhibited a high quality look when polished. Heavy metal leaching concentrations have also been effectively reduced to low levels in glass ceramics.

v. Case studies, predominantly on bricks, demonstrated satisfactory technical performances with SSA in practical situations, though reservations have been raised about the economic viability in a specific case with SSA used as the entire brick feedstock. Issues such as scumming have been overcome by limiting absorption levels, whilst SSA has been combined with a high water content material (water treatment residue) to counteract higher forming water requirements.

REFERENCES

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences*, 71, 2453-2463.

Anderson M. 1999 The use of sewage sludge incinerator ash in brickmaking. *Wastes Management*, August 1999, pg 36.

Anderson M. 2002 Encouraging prospects for recycling incinerated sewage sludge ash (ISSA) into clay-based building products (2002). *Journal of Chemical Technology and Biotechnology*, 77, 352-360.

Anderson M and Skerratt R G. 2003 Variability study of incinerated sewage sludge ash in relation to future use in ceramic brick manufacture. *British Ceramic Transactions*, 102(3), 109-113.

Anderson M, Skerratt R G, Thomas J P and Clay S. 1996 Case study involving using fluidised bed incinerator sludge ash as a partial clay substitute in brick manufacture. *Water Science and Technology*, 34(3-4), 507-515.

Anderson M, Elliott M and Hickson C. 2002 Factory-scale proving trials using combined mixtures of three by-product wastes (including incinerated sewage sludge ash) in clay building bricks. *Journal of Chemical Technology and Biotechnology*, 77, 345-351

Cheeseman C R, Sollars C J and McEntee S. 2003 Properties, microstructure and leaching of sintered sewage sludge ash. *Resources, Conservation and Recycling*, 40, 13-25.

Chen L and Lin D F. 2009 Applications of sewage sludge ash and nano-SiO_2 to manufacture tile as construction material. *Construction and Building Materials*, 23, 3312-3320.

Clean Air Task Force. 2010 *Black Carbon from Brick Kilns*. Available from http://www.catf.us/resources/presentations/files/Black_Carbon_from_Brick_Kilns.pdf [Accessed 20/09/15].

Dayalan J and Beulah M. 2014 Glazed sludge tile. *International Journal of Engineering Research and Applications*, 4(3), 201-204.

DEFRA. 2007 *Characterisation of mineral wastes, resources and processing technologies - Integrated waste management for the production of construction material*. SID 5 Research Project Final Report WRT177 / WR0115.

Donatello S and Cheeseman C. 2013 Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Management*, 33(11), 2328-2340.

Endo H, Nagayoshi Y and Suzuki K. 1997 Production of glass ceramics from sewage sludge. *Water Science & Technology, 36(11), 235-241*.

Environmental Protection Act. 1990 ISBN 0105443905 (SSI 2001/99).

Environmental & Water Technology Centre of Innovation. 2012 *Direct use of sewage sludge ash in paving materials*. Singapore: ECO Industrial Environmental Engineering Pte Ltd.

European Community. 1991 *Council Directive of 21 May 1991 concerning urban waste water treatment 91/271/EEC*, L 135/40.

European Community. 1998 *Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption*, L330/32.

European Community. 1999 C*ouncil Directive 1999/31/EC of 26 April 1999 on the landfill of waste*, L 182/1.

European Community. 2003 *Criteria and procedures for the acceptance of waste at landfills, Annex to Directive 1999/31/EC on the landfill of waste*, L 11/29.

Hnat J G, Mathur A, Simpson J C. 1999 *Manufacture of ceramic tiles from fly ash*. Unites States Patent 5935885, August 10th.

Isa H. 2011 A review of glass-ceramics production from silicate wastes. *International Journal of the Physical Sciences*, 6(30), 6781-6790.

Jamshidi M, Jamshidi A, Mehrdadi N and Pacheco-Torgal F. 2012 Mechanical performance and capillary water absorption of sewage sludge ash concrete (SSAC). *International Journal of Sustainable Engineering*, 5(3), 228-234.

Johnson O A, Napiah M and Kamaruddin I. 2014 Potential uses of waste sludge in construction industry: A review. *Research Journal of Applied Sciences, Engineering and Technology*, 8(4), 565-570.

Kadir A A and Mohajerani A. 2011 Bricks: An excellent building material for recycling wastes - A review. *Proceedings of the IASTED International Conference* July 4 - 6, 2011 Calgary, AB, Canada Environmental Management and Engineering (EME 2011).

Kaneko S, Shindo T, Inokawa A, Hoshino Y, Otsuka T, Wakasugi K and Takikawa M. 1992 *Ceramic tile produced from sludge slag*. United States Patent 5175134, December 29th 1992.

Lin D F and Weng C H. 2001 Use of sewage sludge ash as brick material. *Journal of Environmental Engineering*, 127(10), 922-927.

Lin D F, Luo H L and Sheen Y N. 2005 Glazed tiles manufactured from incinerated sludge ash and clay. *Journal of the Air and Waste Management Association*, 55(2), 163-172.

Lin K L, Chiang K Y and Lin D F. 2006 Effect of heating temperature on the sintering characteristics of sewage sludge ash. *Journal of Hazardous Materials*, B128, 175-181.

Lin D F, Luo H L and Zhang S W. 2007 Effects on nano-SiO_2 on tiles manufactured with clay and incinerated sewage sludge ash. *Journal of Materials in Civil Engineering*, 19(10), 801-808.

Lin D F, Chang W C, Yuan C and Luo H L. 2008 Production and characterization of glazed tiles containing incinerated sewage sludge. *Waste Management*, 28, 502-508.

Luo H L and Lin D F. 2003 Evaluation of color changes in sewage sludge ash brick by using image analysis method. *Practice Periodical of Hazardous, Toxic and Radioactive Waste Management*, 7(4), 214-223.

Merino I, Arévalo L F and Romero F. 2005 Characterization and possible uses of ashes form wastewater treatment plants. *Waste Management*, 25, 1046-1054.

Merino I, Arévalo L F and Romero F. 2007 Preparation and characterization of ceramic products by thermal treatment of sewage sludge ashes mixed with different additives. *Waste Management*, 27, 1829-1844.

Ministry of the Environment. 1991 *Environmental Quality Standards for Soil Pollution*, Japan.

Mödinger F. 2002 New building products: Low density fibre reinforced ceramic matrix composites - CMC containing sewage sludge, ISSA, incinerated sewage sludge ash and other ashes as components. *PROGRES* Barcelona Spain, 14/15th February.

Okufuji T. 1990 Incinerating sewage sludge and producing reusable ash: Japanese experience. *Proceedings of 1990 National Waste Processing Conference – Fourteenth Biennial Conference*, June 3–6, 1990, Long Beach, CA, USA. American Society of Mechanical Engineers (ASME), New York, NY, USA.

Okuno N and Takahashi S. 1997 Full scale application of manufacturing bricks from sewage. *Water Science and Technology*, 36(11), 243.

Okuno N, Ishikawa Y, Shimizu A and Yoshida M. 2004 Utilization of sludge in building material. *Water Science and Technology*, 49(10), 225.232.

Park Y J, Moon S O and Heo J. 2003 Crystalline phase control of glass ceramics obtained from sewage sludge fly ash. *Ceramics International*, 29, 223-227.

Petavratzi E. 2007 *Incinerated sewage sludge ash in facing bricks*. Characterisation of Mineral Wastes, Resources and Processing Technologies - Integrated Waste Management for the Production of Construction Material, WRT 177/WR0115.

Petavratzi E and Barton J. 2007 *Industry Sector Study: Heavy Ceramic (Brick)*. Characterisation of Mineral Wastes, Resources and Processing Technologies - Integrated Waste Management for the Production of Construction Material, WRT 177 / WR0115.

Rawlings R D, Wu J P, Boccaccini A R. 2006 Glass-ceramics: Their production from wastes. A review. *Journal of Materials Science*, 41, 733-761.

Satoshi O and Hiroki H. 1993 *Production of water-permeable block brick from incinerated ash of sewage sludge*. Japan Patent 1993-238802.

Smith A. 2014 *Materials from alternative recycled and secondary sources (MARSS) 2005-2010: A review of the use of non-primary clay raw materials in the UK brick manufacturing sector*. Available from http://www.wienerberger.co.uk/sustainability/sustainability-production/ceram-review-document-on-marss-in-brick-manufacturing.html [Accessed 10/09/2015].

Smol M, Kulczycka J, Henclik A, Gorazda K and Wzorek Z. 2015 The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *Journal of Cleaner Production*, 95, 45-54.

Suzuki S, Tanaka M and T Kaneko. 1997 Glass-ceramic from sewage sludge ash. *Journal of Material Sciences*, 32, 1775-1779.

Tay J H. 1987 Bricks manufactured from sludge. *Journal of Environmental Engineering*, 113(2), 278-284.

Tay J H and Show K Y. 1992 Utilization of municipal wastewater sludge as building and construction materials. *Resources, Conservation and Recycling*, 6, 191-204.

Trauner E J. 1993 Sludge ash bricks fired to above and below ash-vitrifying temperature. *Journal of Environmental Engineering*, 119(3), 506-519.

USEPA. 1972 *Sewage sludge incineration*, Report no. EPA-R2-72-040, PB 211 323.

Vouk D, Nakic D and Stirmer N. 2015 Reuse of sewage sludge - problems and possibilities. *Proceedings Industrial waste, wastewater treatment and valorisation*, Moustakas, Konstantinos (ed.). - Athens: National Technical University of Athens, 1-21.

Wienerberger. 2012 *The use of materials from alternative, recycled and secondary sources in the manufacture of clay bricks*. Available from http://www.wienerberger.co.uk/use-of-marss-in-manufacture-of-clay-bricks-full-version.html [Accessed 09/09/15]

Wystalska K, Sobik-Szoltysek J and Bien J B. 2013 Vitrification and devitrification of ash after sewage sludge combustion. *Annual Set The Environment Protection Rocznik Ochrona Srodowiska*, 15, 181-191.

Yoon S D and Yun Y H. 2011 Preparation of glass ceramics from sludge bottom ash and waste glass. *Journal of Ceramic Processing Research*, 12 (4), 361-364.

Zhang Z, Li A, Yin Y and Zhao L. 2013 Effect of crystallization time on behaviours of glass-ceramic produced from sludge incineration ash. *Procedia Environmental Sciences*, 18, 788-793.

Zhang Z, Zhang L, Yin Y, Liang X and Li A. 2015 The recycling of incinerated sewage sludge ash as a raw material for CaO-Al_2O_3-SiO_2-P_2O_5 glass ceramic production. *Environmental Technology*, 36(9), 1098-1103.

SUPPLEMENTARY DATA

Appendix A: Material Description

Anderson M. 1999 The use of sewage sludge incinerator ash in brickmaking, *Wastes Management* August 1999, pg 36.

Anderson M. 2002 Encouraging prospects for recycling incinerated sewage sludge ash (ISSA) into clay-based building products. *Journal of Chemical Technology and Biotechnology*, 77, 352-360.

Anderson M and Skerratt R G. 2003 Variability study of incinerated sewage sludge ash in relation to future use in ceramic brick manufacture. *British Ceramic Transactions*, 102(3), 109-113.

Anderson M, Elliott M and Hickson C. 2002 Factory-scale proving trials using combined mixtures of three by-product wastes (including incinerated sewage sludge ash) in clay building bricks. *Journal of Chemical Technology and Biotechnology*, 77, 345-351

Suzuki S, Tanaka M and T Kaneko. 1997 Glass-ceramic from sewage sludge ash. *Journal of Material Sciences*, 32, 1775-1779.

Appendix B: Fineness and Particle Size Distribution

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences*, 71, 2453-2463.

Anderson M and Skerratt R G. 2003 Variability study of incinerated sewage sludge ash in relation to future use in ceramic brick manufacture, *British Ceramic Transactions*, 102(3), 109-113.

Coutand M, Cyr M and Clastres P. 2006 Use of sewage sludge ash as mineral admixture in mortars, Construction Materials, 159, Issue CM4, 153-162.

Cyr M, Coutand M and Clastres P. 2007 Technological and environmental behaviour of sewage sludge ash (SSA) in cement based materials, Cement and Concrete Research, 37, 1278-1289.

De Lima J F, Ingunza D and Del Pilar M. 2015 Effects of sewage sludge ash addition in Portland cement concretes, *International conference on civil, materials and environmental sciences* (CMES 2015), London 13-14th March, Atlantis Press, 189-191.

Donatello S, Tong D and Cheeseman C R. 2010 Production of technical grade phosphoric acid from incinerator sewage sludge ash (ISSA), Waste Management, 30, 1634-1642.

Donatello S, Tyrer M and Cheeseman C R. 2010 Comparison of test methods to assess pozzolanic activity, Cement & Concrete Composites, 32, 121-127.

Donatello S, Freeman-Pask A and Cheeseman C R. 2010 Effect of milling and acid washing on the pozzolanic activity of incinerator sewage sludge ash. *Cement and Concrete Composites*, 32, 54-61.

Environmental & Water Technology Centre of Innovation. 2012 *Direct use of sewage sludge ash in paving materials*. Singapore: ECO Industrial Environmental Engineering Pte Ltd.

Fontes C M A, Barbosa M C, Filho R D and Gonçalves J P. 2004 Potentiality of sewage sludge ash as mineral additive in cement mortar and high performance concrete. *Proceedings of the International RILEM Conference on the Use of Recycled Materials in Buildings and Structures* 8-11 November 2004, 797-806, RILEM Publications.

Franz M. 2008 Phosphate fertilizer from sewage sludge ash (SSA). *Waste Management*, 28, 1809-1818.

Geyer A L B, Molin D D and Consoli N C. 2002 Study of use of sewage sludge ash as addition in concrete. *High Performance Concrete and Performance and Quality of Concrete Structures: Proceedings of Third International Conference*, 111-124, CANMET/American Concrete Institute.

Halliday J E. 2008 Properties of sewage sludge ash and its potential use in concrete. In: R DHIR ed. *Role for Concrete in Global Development*, IHS BRE Press, 235-244.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Jamshidi M, Jamshidi A, Mehrdadi N and Pacheco-Torgal F. 2012 Mechanical performance and capillary water absorption of sewage sludge ash concrete (SSAC). *International Journal of Sustainable Engineering*, 5(3), 228-234.

Khanbilvardi R and Afshari-Tork S. 1995 Sludge ash as fine aggregate for concrete mix. *Journal of Environmental Engineering*, 121(9), 633-638.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies*, 20(2), 365-370.

Krejcirikova B. 2015 *Zero Waste Materials*. Presentation at Technical University of Denmark. Available from https://tu-dresden.de/die_tu_dresden/fakultaeten/fakultaet_architektur/ibk/institute/events/2013_entool/401_ZeroWasteMaterials-BarboraKrejcirikova.pdf [Accessed 20/09/15]

Lin D F, Lin K L and Chang W C, Luo H L and Cai M Q. 2008 Improvements of nano-SiO2 on sludge/fly ash mortar. *Waste Management*, 28, 1081-1087.

Ottosen L M, Jensen P E and Kirkelund M. 2014 Electrodialytic separation of phosphorus and heavy metals from two types of sewage sludge ash. *Separation Science and Technology*, 49(12), 1910-1920.

Pan S C, Tseng D H, Lee C C and Lee C. 2003 Influence of fineness of sewage sludge ash on the mortar properties. *Cement and Concrete Research*, 33, 1749-1754.

Perez Carrion M, Baeza-Brotons F, Paya J, Saval J M, Zornoza E, Borrachero M V and Garces P. 2013 Potential use of sewage sludge ash (SSA) as a cement replacement in precast concrete blocks. *Materials de Construccion*, 64, 313.

Sato Y, Oyamada T and Hanehara S. 2013 Applicability of sewage sludge ash (SSA) for paving materials: A study on using SSA as filler for asphalt mixture and base course material. *Third International Conference on Sustainable Construction Materials and Technologies*, August 2013, Kyoto, Japan.

Tseng D H and Pan S C. 2000 Enhancement of pozzolanic activity and morphology of sewage sludge ash by calcinations. *Journal of the Chinese Institute of Environmental Engineering*, 10(4), 261-270.

Wang K S, Chiou I J, Chen C H and Wang D. 2005 Lightweight properties and pore structure of foamed material made from sewage sludge ash. *Construction and Building Materials*, 19, 627-633.

Wang K S, Tseng C J, Chiou I J and Shih M H. 2005 The thermal conductivity mechanism of sewage sludge ash lightweight materials. *Cement and Concrete Research*, 35, 803-809.

Appendix C: Density

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences*, 71, 2453-2463.

Bapat J D. 2013 *Mineral Admixtures in Cement and Concrete*. Boca Raton: CRC Press.

Barton J. 2007 *Case study: BITUBLOCK - a novel construction unit using 100% waste derived aggregate*. Characterisation of Mineral Wastes, Resources and Processing Technologies - Integrated Waste Management for the Production of Construction Material, WRT 177 / WR0115.

Coutand M, Cyr M and Clastres P. 2006 Use of sewage sludge ash as mineral admixture in mortars. *Construction Materials*, 159, Issue CM4, 153-162.

Cyr M, Coutand M and Clastres P. 2007 Technological and environmental behaviour of sewage sludge ash (SSA) in cement based materials. *Cement and Concrete Research*, 37, 1278-1289.

Dayalan J and Beulah M. 2014 Glazed sludge tile. *International Journal of Engineering Research and Applications*, 4 (3), 201-204.

De Lima J F, Ingunza D and Del Pilar M. 2015 Effects of sewage sludge ash addition in Portland cement concretes. *International conference on civil, materials and environmental sciences* (CMES 2015), London 13-14th March, Atlantis Press, 189-191.

Donatello S, Tyrer M and Cheeseman C R. 2010 Comparison of test methods to assess pozzolanic activity. *Cement & Concrete Composites*, 32, 121-127.

Donatello S, Freeman-Pask A and Cheeseman C R. 2010 Effect of milling and acid washing on the pozzolanic activity of incinerator sewage sludge ash. *Cement and Concrete Composites*, 32, 54-61.

Federal Highway Administration. 1997 *User guidelines for waste and by-product materials in pavement construction*. USA: Federal Highway Administration (FHWA-RD-97-148).

Forth J P, Zoorob S E and Thanaya I N A. 2006 Development of bitumen-bound waste aggregate building blocks. *Proceedings of the Institution of Civil Engineers: Construction Materials*, 159, 23-32.

Geyer A L B, Molin D D and Consoli N C. 2002 Study of use of sewage sludge ash as addition in concrete. *High Performance Concrete and Performance and Quality of Concrete Structures: Proceedings of Third International Conference*, 111-124, CANMET/American Concrete Institute.

Halliday J E. 2008 Properties of sewage sludge ash and its potential use in concrete. In: R DHIR ed. *Role for Concrete in Global Development*, IHS BRE Press, 235-244.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Jamshidi M, Jamshidi A, Mehrdadi N and Pacheco-Torgal F. 2012 Mechanical performance and capillary water absorption of sewage sludge ash concrete (SSAC). *International Journal of Sustainable Engineering*, 5(3), 228-234.

Kjersgaard D. 2007 The reuse of bio ash for the production of concrete. A Danish case study. *IWA Specialist Conference on Wastewater Biosolids*, 24-27 June, Moncton, New Brunswick, Canada.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies*, 20(2), 365-370.

Lin K L, Lan J Y, Luo K W, Chang J C and Sie J P. 2014 Effects of Sintering Temperature on Water Retention Characteristics of Sewage Sludge Ash- Diatomite Based Porous Ceramics. *4th International Conference on Future Environment and Energy V61*, Singapore 2014, LACSIT Press.

Luo H L, Chang W C, Lin D F. 2009 The effects of different types of nano-silicon dioxide additives on the properties of sludge ash mortar. *Journal of the Air & Waste Management Association*, 59(4), 440-446.

Merino I, Arévalo L F and Romero F. 2007 Preparation and characterization of ceramic products by thermal treatment of sewage sludge ashes mixed with different additives, *Waste Management.* 27, 1829-1844.

NCHRP. 2013 *Recycled Materials and Byproducts in Highway Applications*, Volume 3: Non-coal combustion byproducts, Synthesis 435.

Pade C, Jakobsen U H. 2007 Bio ashes from Lynetten and Avedore waste water treatment plants: Documentation of ash properties. *IWA Specialist Conference on Wastewater Biosolids*, 24-27 June, Moncton, New Brunswick, Canada.

Pan S C, Tseng D H, Lee C C and Lee C. 2003 Influence of fineness of sewage sludge ash on the mortar properties. *Cement and Concrete Research*, 33, 1749-1754.

Pinarli V and Kaymal G. 1994 An innovative sludge disposal option-reuse of sludge ash by incorporation in construction materials. *Environmental Technology*, 15(9), 843-852.

Sato Y, Oyamada T and Hanehara S. 2013 Applicability of sewage sludge ash (SSA) for paving materials: A study on using SSA as filler for asphalt mixture and base course material. *Third International Conference on Sustainable Construction Materials and Technologies,* August 2013, Kyoto, Japan.

Tay J H. 1987 Sludge ash as filler for Portland cement concrete. *Journal of Environmental Engineering*, 113(2), 345-351.

Tay J H and Show K Y. 1992 Utilization of municipal wastewater sludge as building and construction materials. *Resources, Conservation and Recycling*, 6, 191-204.

Tenza-Abril A J, Saval J M and Cuenca A. 2014 Using sewage sludge ash as filler in bituminous mixes. *Journal of Materials in Civil Engineering*, 04014141-1-9.

Tseng D H and Pan S C. 2000 Enhancement of pozzolanic activity and morphology of sewage sludge ash by calcinations. *Journal of the Chinese Institute of Environmental Engineering*, 10(4), 261-270.

USEPA. 1972 *Sewage sludge incineration.* Report no. EPA-R2-72-040, PB 211 323.

Vouk D, Nakic D and Stirmer N. 2015 Reuse of sewage sludge - problems and possibilities. *Proceedings Industrial waste, wastewater treatment and valorisation*, Moustakas, Konstantinos (ed.) Athens: National Technical University of Athens, 1-21.

Wang K S, Tseng C J, Chiou I J and Shih M H. 2005 The thermal conductivity mechanism of sewage sludge ash lightweight materials. *Cement and Concrete Research*, 35, 803-809.

Yip W K and Tay J H. 1990 Aggregate made from incinerated sludge residue. *Journal of Materials in Civil Engineering*, 2(2), 84-93.

Appendix D: Morphology

Bapat J D. 2013 *Mineral Admixtures in Cement and Concrete*. Boca Raton: CRC Press.

Chiou I J, Wang K S, Chen C H and Lin Y T. 2006 Lightweight aggregate made from sewage sludge and incinerated ash. *Waste Management*, 26, 1453-1461.

Coutand M, Cyr M and Clastres P. 2006 Use of sewage sludge ash as mineral admixture in mortars. *Construction Materials*, 159, Issue CM4, 153-162.

De Lima J F, Ingunza D and Del Pilar M. 2015 Effects of sewage sludge ash addition in Portland cement concretes. *International conference on civil, materials and environmental sciences* (CMES 2015), London 13-14th March, Atlantis Press, 189-191.

Dhir R K, Dyer T D, Halliday J E and Paine K A. 2002 *Value added recycling of incinerator ashes*. UK: Concrete Technology Unit (No. 39/3/476 CC 1683).

Elouear Z, Bouzid J and Boujelben N. 2010 Removal of nickel and cadmium from aqueous solutions by sewage sludge ash: study in single and binary systems. *10th World Wide Workshop for Young Environmental Scientists,* Arcueil, France, 31st May – 4th June.

Halliday J E. 2008 Properties of sewage sludge ash and its potential use in concrete. In: R DHIR ed. *Role for Concrete in Global Development*, IHS BRE Press, 235-244.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies*, 20(2), 365-370.

Latosinska J. 2014 The evaluation of the impact of sewage sludge ash modification on leaching of heavy metals. *Advances in Civil and Environmental Engineering*, 1(1), 27-42.

Latosinska J and Gawdzik J. 2012 Effect of incineration temperature on the mobility of heavy metals in sewage sludge ash. *Environment Protection Engineering*, 38(3), 31-44.

Monzo J, Payá J, Borrachero M V and Córcoles A. 1996 Use of sewage sludge ash (SSA) – Cement admixtures in mortars. *Cement and Concrete Research*, 26(9), 1389-1398.

Monzo J, Paya J, Borrachero M V, Morenilla J J, Bonilla M and Calderon P. 2004 Some strategies for reusing residues from waste water treatment plants: preparations of binding materials. *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures* 8-11 November 2004, Barcelona, Spain.

Morais L C, Dweck J, Goncalves E M and Buchler P M. 2005 An experimental study of sewage sludge incineration. *Environmental Technology*, 27(9), 1047-1051.

Morais L C, Dweck J, Valenzuela F R, Goncalves E M and Buchler P M. 2006 *Characterization of sludge after thermal treatment*. Available from https://www.ipen.br/biblioteca/cd/ptech/2005/PDF/22_14.PDF [Accessed 20/05/15]

Pade C and Jakobsen U H. 2007 Bio ashes from Lynetten and Avedore waste water treatment plants: Documentation of ash properties. *IWA Specialist Conference on Wastewater Biosolids*, 24-27 June, Moncton, New Brunswick, Canada.

Paya J, Monzó J, Borrachero M V, Amahjour F, Girbés, Velázquez S and Ordóňez L M. 2002 Advantages in the use of fly ashes in cements containing pozzolanic combustion residues: silica fume, sewage sludge ash, spend fluidized bed catalyst and rice husk ash. *Journal of Chemical Technology and Biotechnology*, 77, 331-335.

Perez Carrion M, Baeza-Brotons F, Paya J, Saval J M, Zornoza E, Borrachero M V and Garces P. 2013 Potential use of sewage sludge ash (SSA) as a cement replacement in precast concrete blocks. *Materials de Construccion*, 64, 313.

Sato Y, Oyamada T, Hanehara S and Sasaki T. 2012 The characteristics of ash of sewage sludge (SSA) in iwate prefecture and application of SSA for asphalt mixture. *Journal of The Mining and Materials Processing Institute of Japan*, 128, 519-525.

Sato Y, Oyamada T and Hanehara S. 2013 Applicability of sewage sludge ash (SSA) for paving materials: A study on using SSA as filler for asphalt mixture and base course material. *Third International Conference on Sustainable Construction Materials and Technologies*, August 2013, Kyoto, Japan.

Vouk D, Nakic D and Stirmer N. 2015 Reuse of sewage sludge - problems and possibilities. *Proceedings Industrial waste, wastewater treatment and valorisation*, Moustakas, Konstantinos (ed.). - Athens: National Technical University of Athens, 1-21.

Wang K S, Chiou I J, Chen C H and Wang D. 2005 Lightweight properties and pore structure of foamed material made from sewage sludge ash. *Construction and Building Materials*, 19, 627-633.

Wang K S, Tseng C J, Chiou I J And Shih M H. 2005 The thermal conductivity mechanism of sewage sludge ash lightweight materials. *Cement and Concrete Research*, 35, 803-809.

Zeedan S R. 2010 Utilizing new binder materials for green building has zero waste by recycling slag and sewage sludge ash. *Proceedings of the Tenth International Conference for Enhanced Building Operations,* Kuwait, October 26-28, 2010.

Appendix E: Absorption

Bhatty J I and Reid K J. 1989 Moderate strength concrete from lightweight sludge ash aggregates. *The International Journal of Cement Composites and Lightweight Concrete*, 11(3), 179-187.

Forth J P, Zoorob S E and Thanaya I N A. 2006 Development of bitumen-bound waste aggregate building blocks. *Proceedings of the Institution of Civil Engineers: Construction Materials,* 159, 23-32.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Tay J H and Yip W K. 1989 Sludge ash as lightweight concrete material. *Journal of Environmental Engineering*, 115(1), 56-64.

Appendix F: Oxide Composition

Adam C, Peplinski B, Michaelis M, Kley G and Simon F G. 2009 Thermochemical treatment of sewage sludge ashes for phosphorus recovery. *Waste Management*, 29, 1122-1128.

Adam C, Brenneis R, Adamczyk B and Simon F G. 2013 Recycling of waste materials by thermochemical treatment. *Available from http://www.iswa.org/uploads/tx_iswaknowledgebase/Adam.pdf [Accessed 20/09/15]*

Al Sayed M H, Madany I M and Buali A R M. 1995 Use of sewage sludge ash in asphaltic paving mixes in hot regions. *Construction and Building Materials*, 9(1), 19-23.

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences*, 71, 2453-2463.

Anderson M and Skerratt R G. 2003 Variability study of incinerated sewage sludge ash in relation to future use in ceramic brick manufacture. *British Ceramic Transactions*, 102(3), 109-113.

Anderson M, Elliott M and Hickson C. 2002 Factory-scale proving trials using combined mixtures of three by-product wastes (including incinerated sewage sludge ash) in clay building bricks. *Journal of Chemical Technology and Biotechnology*, 77, 345-351

Baeza F, Paya J, Galao O, Saval J M and Garces P. 2014 Blending of industrial waste from different sources as partial substitution of Portland cement in pastes and mortars. *Construction and Building Materials*, 66, 645-653.

Baeza-Brotons F, Garces P, Paya J and Saval J M. 2014 Portland cement systems with addition of sewage sludge ash. Application in concretes for the manufacture of blocks. *Journal of Cleaner Production*, 82, 112-124.

Bhatty J I, Malisci A, Iwasaki I and Reid K J. 1992 Sludge ash pellets as coarse aggregate in concrete. *Journal of Cement. Concrete and Aggregates*, 14(1), 55-61.

Chang F C, Lin J D, Tsai C C and Wang K S. 2010 Study on cement mortar and concrete made with sewage sludge ash. Water Science and Technology, 62(7), 1689-1693.

Chen M, Blanc D, Mehu J, Gautier M, Gourdon R and Jayr E. 2012 Pilot-scale leaching behaviour study of ready-mix concrete containing Ash from sewage sludge thermal treatment.

CIRIA. 2004 *Use of sewage sludge in construction*. London: CIRIA C608.

Damtoft J S, Glavind M, Munch-Petersen C. 2001 Danish Centre for Green Concrete. *Proceedings of CANMET/ACI International Conference,* San Fransisco, September 2001.

De Lima J F, Ingunza D and Del Pilar M. 2015 Effects of sewage sludge ash addition in Portland cement concretes. *International conference on civil, materials and environmental sciences* (CMES 2015), London 13-14th March, Atlantis Press, 189-191.

Donatello S, Tyrer M and Cheeseman C R. 2010 EU landfill waste acceptance criteria and EU hazardous waste directive compliance testing of incinerated sewage sludge ash. *Waste Management*, 30, 63-71.

Dyer T D, Halliday J E and Dhir R K. 2011 Hydration chemistry of sewage sludge ash used as a cement component. *Journal of Materials in Civil Engineering*, 23, 648-655.

Elouear Z, Bouzid J and Boujelben N. 2010 Removal of nickel and cadmium from aqueous solutions by sewage sludge ash: study in single and binary systems. *10th World Wide Workshop for Young Environmental Scientists,* Arcueil, France, 31st May – 4th June.

Endo H, Nagayoshi Y and Suzuki K. 1997 Productoin of glass ceramics from sewage sludge. *Water Science & Technology, 36 (11), 235-241.*

EU Life. 2007 *Project BioCrete – Chemical Composition of European bio ashes*. EU Life Project. Available from http://www.biocrete.dk/english/20186 [Accessed 5th May 2015].

Fontes C M A, Barbosa M C, Filho R D and Gonçalves J P. 2004 Potentiality of sewage sludge ash as mineral additive in cement mortar and high performance concrete. *Proceedings of the International RILEM Conference on the Use of Recycled Materials in Buildings and Structures* 8-11 November 2004, 797-806, RILEM Publications.

Franz M. 2008 Phosphate fertilizer from sewage sludge ash (SSA). *Waste Management*, 28, 1809-1818.

Garcés P, Carrión M P, Alcocel E G, Payá J, Monzo J and Borrachero M V. 2008 Mechanical and physical properties of cement blended with sewage sludge ash. *Waste Management*, 28, 2495-2502.

Geyer A L B, Molin D D and Consoli N C. 2002 Study of use of sewage sludge ash as addition in concrete. *High Performance Concrete and Performance and Quality of Concrete Structures: Proceedings of Third International Conference*, 111-124, CANMET/American Concrete Institute.

Haglund J E, Hultgren J, Karlsson B and Arstrom J. 1997 *Förstudie angående slamförbränning vid Stockholm Vatten.* Stockholm Vatten, R. Nr 10.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Hnat J G, Mathur A, Simpson J C. 1999 *Manufacture of ceramic tiles from fly ash.* Unites States Patent 5935885, August 10th 1999.

Hong K J, Tarutani N, Shinya Y and Kajiuchi T. 2005 Study on the recovery of phosphorus from waste-activated sludge incinerator ash. *Journal of Environmental Science and Health,* 40, 617-631.

Hu S H and Hu S C. 2014 Application of magnetically modified sewage sludge ash (SSA) in ionic dye adsorption. *Journal of the Air & Waste Management Association,* 64(2), 141-149.

Hu S H, Hu S C and Fu Y P. 2012 Recycling technology – Artificial lightweight aggregates synthesized from sewage sludge and its ash at lowered comelting temperature. *Environmental Progress & Sustainable Energy,* 32(3), 740-748.

Hu S H, Hu S C and Fu Y P. 2012 Resource recycling through artificial lightweight aggregates from sewage sludge and derived ash using boric acid flux to lower co-melting temperature. *Journal of the Air and Waste Management Association,* 62(2), 262-269.

Huang Y C and Li K C. 2003 Effect of reducing conditions on sludge melting process. *Chemosphere,* 50, 1063-1068.

Jamshidi M, Jamshidi A, Mehrdadi N and Pacheco-Torgal F. 2012 Mechanical performance and capillary water absorption of sewage sludge ash concrete (SSAC). *International Journal of Sustainable Engineering,* 5(3), 228-234.

Kikuchi R. 2001 Recycling of municipal solid waste for cement production: pilot-scale test for transforming incineration ash of solid waste into cement clinker. *Resources, Conservation and Recycling,* 31, 137-147.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies,* 20(2), 365-370.

Kozai N, Suzuki S, Aoyagi N, Sakamoto F and Ohnuki T. 2015 Radioactive fallout cesium in sewage sludge ash produced after the Fukushima Daiichi nuclear accident. *Water Research,* 68, 616-626.

Lam C H K, Barford J P and Mckay G. 2010 Utilization of incineration waste ash residues in Portland cement clinker. *Chemical Engineering Transactions,* 21, 757-762.

Latosinska J. 2014 The evaluation of the impact of sewage sludge ash modification on leaching of heavy metals. *Advances in Civil and Environmental Engineering,* 1(1), 27-42.

Levlin E. 1999 *Resources recovery from incineration ashes*. Proceedings of a Polish-Swedish seminar August 24 1999 Stockholm, 43-53 (Report No. 5, TRITA-AMI REPORT 3063, ISBN 91-7170-439-6).

Li R, Zhao W, Li Y, Wang W and Zhu X. 2015 Heavy metal removal and speciation transformation through the calcinations treatment of phosphorus-enriched sewage sludge ash. *Journal of Hazardous Materials,* 283, 423-431.

Lin K L and Lin C Y. 2004 Hydration properties of eco-cement pastes from waste sludge ash clinkers. *Journal of the Air & Waste Management Association,* 54(12), 1534-1542.

Lin K L and Lin C Y. 2005 Hydration characteristics of waste sludge ash utilized as raw cement material. *Cement and Concrete Research,* 35, 1999-2007.

Lin D F, Luo H L and Sheen Y N. 2005 Glazed tiles manufactured from incinerated sludge ash and clay. *Journal of the Air and Waste Management Association,* 55(2), 163-172.

Lin K L, Chiang K Y and Lin D F. 2006 Effect of heating temperature on the sintering characteristics of sewage sludge ash. *Journal of Hazardous Materials,* B128, 175-181.

Lin D F, Lin K L and Luo H L. 2007 A comparison between sludge ash and fly ash on the improvement in soft soil. *Journal of the Air & Waste Management Association*, 57(1), 59-64.

Lin D F, Lin K L and Chang W C, Luo H L and Cai M Q. 2008 Improvements of nano-SiO_2 on sludge/fly ash mortar. *Waste Management*, 28, 1081-1087.

Lin K L. Huang W J, Chen K C and Chow J D. 2009 Behaviour of heavy metals immobilized by co-melting treatment of sewage sludge ash and municipal solid waste incinerator fly ash. *Waste Management & Research*, 27, 660-667.

Lin K L, Lan J Y, Luo K W, Chang J C and Sie J P. 2014 Effects of Sintering Temperature on Water Retention Characteristics of Sewage Sludge Ash- Diatomite Based Porous Ceramics. *4th International Conference on Future Environment and Energy V61*, Singapore 2014, LACSIT Press.

Mahieux P Y, Aubert J E, Cyr M, Coutand M and Husson B. 2010 Quantitative mineralogical composition of complex mineral wastes – Contribution of the Rietveld method. *Waste Management*, 30, 378-388.

Merino I, Arévalo L F and Romero F. 2005 Characterization and possible uses of ashes form wastewater treatment plants. *Waste Management*, 25, 1046-1054.

Merino I, Arévalo L F and Romero F. 2007 Preparation and characterization of ceramic products by thermal treatment of sewage sludge ashes mixed with different additives, *Waste Management.* 27, 1829-1844.

Monzo J, Payá J, Borrachero M V and Córcoles A. 1996 Use of sewage sludge ash (SSA) – Cement admixtures in mortars. *Cement and Concrete Research*, 26(9), 1389-1398.

Monzo J, Paya J, Borrachero M V, Bellver A and Peris-Mora E. 1997 Study of cement-based mortars containing Spanish ground sewage sludge ash. In Goumans et al. (eds.) *Waste Materials in Construction: Putting Theory into Practice*, 349-354, Elsevier.

Monzo J, Paya J, Borrachero M V, Morenilla J J, Bonilla M and Calderon P. 2004 Some strategies for reusing residues from waste water treatment plants: preparations of binding materials. *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures* 8-11 November 2004, Barcelona, Spain.

Morais L C, Dweck J, Goncalves E M and Buchler P M. 2005 An experimental study of sewage sludge incineration. *Environmental Technology*, 27(9), 1047-1051.

Morais L C, Dweck J, Valenzuela F R, Goncalves E M and Buchler P M. 2006 *Characterization of sludge after thermal treatment*. Available from https://www.ipen.br/biblioteca/cd/ptech/2005/PDF/22_14.PDF [Accessed 20/05/15]

Morais L C, Dweck J, Campos V and Buchler P M. 2009 Characterization of sewage sludge ashes to be used as a ceramic raw material. *Chemical Engineering Transactions*, 17, 1813-1818.

Nomura K. 1998 *Adoption of melting furnace and sludge utilization in Kyoto City*. Veröffentlichungen des Institutes für Siedlungswasserwirtschaft und Abfalltechink der Universität Hannover, 107, ISBN 3-921 421-36-5

Ohbuchi A, Sakamoto J, Kitano M and Nakamura T. 2008 X-ray fluorescence analysis of sludge ash from sewage disposal plant. *X-Ray Spectrometry*, 37, 544-550.

Okufuji T. 1990 Incinerating sewage sludge and producing reusable ash: Japanese experience. *Proceedings of 1990 National Waste Processing Conference – Fourteenth*

Biennial Conference, June 3–6, 1990, Long Beach, CA, USA. American Society of Mechanical Engineers (ASME), New York, NY, USA

Ozaki M, Watanabe H, Weibusch B. 1997 Characteristics of heavy metals release from incinerated ash, melted slag and their re-products. *Water Science & Technology*, 36(11), 267-274.

Pade C, Jakobsen U H. 2007 Bio ashes from Lynetten and Avedore waste water treatment plants: Documentation of ash properties. *IWA Specialist Conference on Wastewater Biosolids*, 24-27 June, Moncton, New Brunswick, Canada.

Park Y J, Moon S O and Heo J. 2003 Crystalline phase control of glass ceramics obtained from sewage sludge fly ash. *Ceramics International*, 29, 223-227.

Perez Carrion M, Baeza-Brotons F, Paya J, Saval J M, Zornoza E, Borrachero M V and Garces P. 2013 Potential use of sewage sludge ash (SSA) as a cement replacement in precast concrete blocks. *Materials de Construccion*, 64, 313.

Pinarli V and Kaymal G. 1994 An innovative sludge disposal option-reuse of sludge ash by incorporation in construction materials. *Environmental Technology*, 15(9), 843-852.

Rapf M, Raupenstrauch H, Cimatoribus C and Kranert M. 2012 *A new thermo-chemical approach for the recovery of phosphorus from sewage sludge*. European Commission CORDIS Project. Available from http://www.vivis.de/phocadownload/2012_wm/2012_WM_691_698_Rapf.pdf [Accessed 10 May 2015]

Sato Y, Oyamada T, Hanehara S and Sasaki T. 2012 The characteristics of ash of sewage sludge (SSA) in iwate prefecture and application of SSA for asphalt mixture. *Journal of The Mining and Materials Processing Institute of Japan*, 128, 519-525.

Schaum C, Cornel P and Jardin N. 2011 *Phosphorus recovery from sewage sludge ash – a wet chemical approach*, Technische Universität Darmstadt, Germany. Available from http://www.bvsde.paho.org/bvsaar/cdlodos/pdf/phosphorusrecovery583.pdf [Accessed 17 May 2013].

Stark K, Plaza E and Hultman B. 2006 Phosphorus release from ash, dried sludge and sludge residue from supercritical water oxidation by acid or base. *Chemosphere*, 62, 827-832.

Suzuki S, Tanaka M and T Kaneko. (1997) Glass-ceramic from sewage sludge ash. *Journal of Material Sciences*, 32, 1775-1779.

Takahasi H, Asada S, Takahashi S, Ishida S, Takeuchi N and Wakamatu M. 1997 Formation mechanism of black core in sintered red brick using incinerated ash of sewage sludge. *Journal of the Society of Material Sciences Japan*, 46(7), 834-838.

Takahashi M, Kato S, Shima H, Sarai E, Ichioka T, Hatyakawa S and Miyajiri H. 2001 Technology for recovering phosphorus from incinerated wastewater treatment sludge. *Chemosphere*, 44, 23-29.

Takaoka M, Takeda N and Miura S. 1997 The behaviour of heavy metals and phosphorus in an ash melting process. *Water Science and Technology*, 36(11), 275-282.

Takeuchi N, Takahashi H, Ishida S, Takahashi S and Wakamatsu M. 1999 Effect of firing atmosphere on extraordinary expansion of sintered brick from incinerated ash of sewage sludge. *Journal of the Ceramic Society of Japan*, 107(6), 551-554.

Tantawy M A, El-Roudi A M, Abdalla E M and Abdelzaher M A. 2012 Evaluation of the pozzolanic activity of sewage sludge ash. *ISRN chemical engineering*, 2012, 1-8.

Tantawy M A, El-Roudi A M, Abdalla E M and Abdelzaher M A. 2013 Fire resistance of sewage sludge ash blended cement pastes. *Journal of Engineering Hindawi Publishing Corporation*, 2013, 1-7.

Tay J H and Show K Y. 1992 Utilization of municipal wastewater sludge as building and construction materials. *Resources, Conservation and Recycling*, 6, 191-204.

Tay J H and Show K Y. 1994 Municipal wastewater sludge as cementitious and blended cement materials. *Cement & Concrete Composites*, 16, 39-48.

Tenza-Abril A J, Saval J M and Cuenca A. 2014 Using sewage sludge ash as filler in bituminous mixes. *Journal of Materials in Civil Engineering*, 04014141-1-9.

Tsai C C, Wang K S and Chiou I J. 2006 Effect of SiO_2 – Al_2O_3 – flux ratio change on the bloating characteristics of lightweight aggregate material produced from recycled sewage sludge. *Journal of Hazardous Materials*, B134, 87-93.

Tseng D H and Pan S C. 2000 Enhancement of pozzolanic activity and morphology of sewage sludge ash by calcinations. *Journal of the Chinese Institute of Environmental Engineering*, 10(4), 261-270.

USEPA. 1972 *Sewage sludge incineration.* Report no. EPA-R2-72-040, PB 211 323.

Vouk D, Nakic D and Stirmer N. 2015 Reuse of sewage sludge - problems and possibilities. *Proceedings Industrial waste, wastewater treatment and valorisation*, Moustakas, Konstantinos (ed.) Athens: National Technical University of Athens, 1-21.

Wang K S and Chiou I J. 2004 Foamed lightweight materials made from mixed scrap metal waste powder and sewage sludge ash. *Waste Management and Research*, 22, 383-389.

Wang K S, Chiou I J, Chen C H and Wang D. 2005 Lightweight properties and pore structure of foamed material made from sewage sludge ash. *Construction and Building Materials*, 19, 627-633.

Wang L, Skjevrak G, Hustad J E and Grønli M G. 2012 Sintering characteristics of sewage sludge ashes at elevated temperatures. *Fuel Processing Technology*, 96, 88-97.

Wiebusch B and Seyfried C F. 1997 Utilization of sewage sludge ashes in the brick and tile industry. *Water Science and Technology*, 36(11), 251-258.

Xu H, He P, Gu W, Wang G and Shao L. 2012 Recovery of phosphorus as struvite from sewage sludge ash. *Journal of Environmental Sciences*, 24(8), 1533-1538.

Yoon S D and Yun Y H. 2011 Preparation of glass ceramics from sludge bottom ash and waste glass. *Journal of Ceramic Processing Research*, 12 (4), 361-364.

Zeedan S R. 2010 Utilizing new binder materials for green building has zero waste by recycling slag and sewage sludge ash. *Proceedings of the Tenth International Conference for Enhanced Building Operations*, Kuwait, October 26-28, 2010.

Zhang Z, Zhang L, Yin Y, Liang X and Li A. 2015 The recycling of incinerated sewage sludge ash as a raw material for CaO-Al_2O_3-SiO_2-P_2O_5 glass ceramic production. *Environmental Technology*, 36(9), 1098-1103.

Zhu J G, Yao Y, Lu Q G, Gao M and Ouyang Z Q. 2015 Experimental investigation of gasification and incineration characteristics of dried sewage sludge in a circulating fluidized bed. *Fuel*, 441-447.

Appendix G: Loss On Ignition

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences,* 71, 2453-2463.

Baeza F, Paya J, Galao O, Saval J M and Garces P. 2014 Blending of industrial waste from different sources as partial substitution of Portland cement in pastes and mortars. *Construction and Building Materials,* 66, 645-653.

Bhatty J I and Reid K J. 1989 Moderate strength concrete from lightweight sludge ash aggregates. *The International Journal of Cement Composites and Lightweight Concrete*, 11(3), 179-187.

De Lima J F, Ingunza D and Del Pilar M. 2015 Effects of sewage sludge ash addition in Portland cement concretes. *International conference on civil, materials and environmental sciences* (CMES 2015), London 13-14th March, Atlantis Press, 189-191.

Forth J P, Zoorob S E and Thanaya I N A. 2006 Development of bitumen-bound waste aggregate building blocks. *Proceedings of the Institution of Civil Engineers: Construction Materials,* 159, 23-32.

Halliday J E. 2008 Properties of sewage sludge ash and its potential use in concrete. In: R DHIR ed. *Role for Concrete in Global Development*, IHS BRE Press, 235-244.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Hu S H and Hu S C. 2014 Application of magnetically modified sewage sludge ash (SSA) in ionic dye adsorption. *Journal of the Air & Waste Management Association,* 64(2), 141-149.

Kjersgaard D. 2007 The reuse of bio ash for the production of concrete. A Danish case study. *IWA Specialist Conference on Wastewater Biosolids,* 24-27 June, Moncton, New Brunswick, Canada.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies*, 20(2), 365-370.

Kruger O, Grabner A and Adam C. 2014 Complete survey of German sewage sludge ash. *Environmental Science & Technology,* 48, 11811-11818.

Lin K L and Lin C Y 2006 Feasibility of using ash from sludge incineration as raw material for eco-cement. *Journal of the Chinese Institute of Environmental Engineering,* 16(1), 39-46.

Merino I, Arévalo L F and Romero F. 2005 Characterization and possible uses of ashes form wastewater treatment plants. *Waste Management*, 25, 1046-1054.

Monzo J, Paya J, Borrachero M V, Bellver A and Peris-Mora E. 1997 Study of cement-based mortars containing Spanish ground sewage sludge ash. In Goumans et al. (eds.) *Waste Materials in Construction: Putting Theory into Practice,* 349-354, Elsevier.

Ottosen L M, Jensen P E and Kirkelund M. 2014 Electrodialytic separation of phosphorus and heavy metals from two types of sewage sludge ash. *Separation Science and Technology,* 49(12), 1910-1920.

Pade C, Jakobsen U H. 2007 Bio ashes from Lynetten and Avedore waste water treatment plants: Documentation of ash properties. *IWA Specialist Conference on Wastewater Biosolids,* 24-27 June, Moncton, New Brunswick, Canada.

Perez Carrion M, Baeza-Brotons F, Paya J, Saval J M, Zornoza E, Borrachero M V and Garces P. 2013 Potential use of sewage sludge ash (SSA) as a cement replacement in precast concrete blocks. *Materials de Construccion*, 64, 313.

Takeuchi N, Takahashi H, Ishida S, Takahashi S and Wakamatsu M. 1999 Effect of firing atmosphere on extraordinary expansion of sintered brick from incinerated ash of sewage sludge. *Journal of the Ceramic Society of Japan*, 107(6), 551-554.

Tantawy M A, El-Roudi A M, Abdalla E M and Abdelzaher M A. 2012 Evaluation of the pozzolanic activity of sewage sludge ash. *ISRN chemical engineering*, 2012, 1-8.

Tay J H and Show K Y. 1994 Municipal wastewater sludge as cementitious and blended cement materials. *Cement & Concrete Composites*, 16, 39-48.

Tay J H and Yip W K. 1989 Sludge ash as lightweight concrete material. *Journal of Environmental Engineering*, 115(1), 56-64.

Appendix H: Mineralogy

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences*, 71, 2453-2463.

Anderson M. 2002 Encouraging prospects for recycling incinerated sewage sludge ash (ISSA) into clay-based building products (2002). *Journal of Chemical Technology and Biotechnology*, 77, 352-360.

Anderson M and Skerratt R G. 2003 Variability study of incinerated sewage sludge ash in relation to future use in ceramic brick manufacture. *British Ceramic Transactions*, 102(3), 109-113.

Anderson M, Elliott M and Hickson C. 2002 Factory-scale proving trials using combined mixtures of three by-product wastes (including incinerated sewage sludge ash) in clay building bricks. *Journal of Chemical Technology and Biotechnology*, 77, 345-351

Atienza-Martinez M, Gea G, Arauzo J, Kersten S R A and Kootstra A M J. 2014 Phosphorus recovery from sewage sludge char ash. *Biomass and Bioenergy*, 65, 42-50.

Baeza F, Paya J, Galao O, Saval J M and Garces P. 2014 Blending of industrial waste from different sources as partial substitution of Portland cement in pastes and mortars. *Construction and Building Materials*, 66, 645-653.

Bapat J D. 2013 *Mineral Admixtures in Cement and Concrete*. Boca Raton: CRC Press.

Bhatty J I and Reid K J. 1989 Moderate strength concrete from lightweight sludge ash aggregates. *The International Journal of Cement Composites and Lightweight Concrete*, 11(3), 179-187.

Coutand M, Cyr M and Clastres P. 2006 Use of sewage sludge ash as mineral admixture in mortars. *Construction Materials*, 159, Issue CM4, 153-162.

Cyr M, Coutand M and Clastres P. 2007 Technological and environmental behaviour of sewage sludge ash (SSA) in cement based materials. *Cement and Concrete Research*, 37, 1278-1289.

De Lima J F, Ingunza D and Del Pilar M. 2015 Effects of sewage sludge ash addition in Portland cement concretes. *International conference on civil, materials and environmental sciences* (CMES 2015), London 13-14th March, Atlantis Press, 189-191.

Dhir R K, Dyer T D, Halliday J E and Paine K A. 2002 *Value added recycling of incinerator ashes*. UK: Concrete Technology Unit (No. 39/3/476 CC 1683).

Donatello S, Tong D and Cheeseman C R. 2010 Production of technical grade phosphoric acid from incinerator sewage sludge ash (ISSA). *Waste Management*, 30, 1634-1642.

Donatello S, Tyrer M and Cheeseman C R. 2010 EU landfill waste acceptance criteria and EU hazardous waste directive compliance testing of incinerated sewage sludge ash. *Waste Management*, 30, 63-71.

Dyer T D, Halliday J E and Dhir R K. 2011 Hydration chemistry of sewage sludge ash used as a cement component. *Journal of Materials in Civil Engineering*, 23, 648-655.

Elouear Z, Bouzid J and Boujelben N. 2010 Removal of nickel and cadmium from aqueous solutions by sewage sludge ash: study in single and binary systems. *10th World Wide Workshop for Young Environmental Scientists*, Arcueil, France, 31st May – 4th June.

Forth J P, Zoorob S E and Thanaya I N A. 2006 Development of bitumen-bound waste aggregate building blocks. *Proceedings of the Institution of Civil Engineers: Construction Materials*, 159, 23-32.

Geyer A L B, Molin D D and Consoli N C. 2002 Study of use of sewage sludge ash as addition in concrete. *High Performance Concrete and Performance and Quality of Concrete Structures: Proceedings of Third International Conference*, 111-124, CANMET/American Concrete Institute.

Gil-Lalaguna N, Sanchez J L, Murillo M B and Gea G. 2015 Use of sewage sludge combustion ash and gasification ash for high-temperature desulphurization of different gas streams. *Fuel*, 141, 99-108.

Guedes P, Couto N, Ottosen L M and Ribeiro A B. 2014 Phosphorus recovery from sewage sludge ash through an electrodialytic process. *Waste Management*, 34, 886-892.

Halliday J E. 2008 Properties of sewage sludge ash and its potential use in concrete. In: R DHIR ed. *Role for Concrete in Global Development*, IHS BRE Press, 235-244.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Hu S H and Hu S C. 2014 Application of magnetically modified sewage sludge ash (SSA) in ionic dye adsorption. *Journal of the Air & Waste Management Association*, 64(2), 141-149.

Kjersgaard D. 2007 The reuse of bio ash for the production of concrete. A Danish case study. *IWA Specialist Conference on Wastewater Biosolids*, 24-27 June, Moncton, New Brunswick, Canada.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies*, 20(2), 365-370.

Kozai N, Suzuki S, Aoyagi N, Sakamoto F and Ohnuki T. 2015 Radioactive fallout cesium in sewage sludge ash produced after the Fukushima Daiichi nuclear accident. *Water Research*, 68, 616-626.

Kruger O, Grabner A and Adam C. 2014 Complete survey of German sewage sludge ash. *Environmental Science & Technology*, 48, 11811-11818.

Lin K L. 2006 Mineralogy and microstructure of sintered sewage sludge ash as lightweight aggregates. *Journal of Industrial and Engineering Chemistry*, 12(3), 425-429.

Lin K L and Lin C Y. 2006 Feasibility of using ash from sludge incineration as raw material for eco-cement. *Journal of the Chinese Institute of Environmental Engineering*, 16(1), 39-46.

Lin K L, Chiang K Y and Lin C Y. 2005 Hydration characteristics of waste sludge ash that is reused in eco-cement clinkers. *Cement and Concrete Research*, 35, 1074-1081.

Lin K L, Chang W C, Lin D F, Luo H L and Tsai M C. 2008 Effects of nano-SiO_2 on sludge ash-cement mortar. *Journal of Environmental Management*, 88, 708-714.

Lin K L. Huang W J, Chen K C and Chow J D. 2009 Behaviour of heavy metals immobilized by co-melting treatment of sewage sludge ash and municipal solid waste incinerator fly ash. *Waste Management & Research*, 27, 660-667.

Lin K L, Lin D F and Luo H L. 2014 *Sewage sludge ash on pozzolanic reaction of co-melted slag blended cement*. Available from http://www.researchgate.net/profile/Kae-Long_Lin/publication/228539727_Sewage_Sludge_Ash_on_Pozzolanic_Reaction_of_Co-melted_Slag_Blended_Cement/links/02e7e5264da1889566000000.pdf [Accessed 10th May 2015].

Mahieux P Y, Aubert J E, Cyr M, Coutand M and Husson B. 2010 Quantitative mineralogical composition of complex mineral wastes – Contribution of the Rietveld method. *Waste Management*, 30, 378-388.

Merino I, Arévalo L F and Romero F. 2005 Characterization and possible uses of ashes form wastewater treatment plants. *Waste Management*, 25, 1046-1054.

Monzo J, Paya J, Borrachero M V, Bellver A and Peris-Mora E. 1997 Study of cement-based mortars containing Spanish ground sewage sludge ash. In Goumans et al. (eds.) *Waste Materials in Construction: Putting Theory into Practice*, 349-354, Elsevier.

Morais L C, Dweck J, Goncalves E M and Buchler P M. 2005 An experimental study of sewage sludge incineration. *Environmental Technology*, 27(9), 1047-1051.

Ottosen L M, Jensen P E and Kirkelund M. 2014 Electrodialytic separation of phosphorus and heavy metals from two types of sewage sludge ash. *Separation Science and Technology*, 49(12), 1910-1920.

Pade C, Jakobsen U H. 2007 Bio ashes from Lynetten and Avedore waste water treatment plants: Documentation of ash properties. *IWA Specialist Conference on Wastewater Biosolids*, 24-27 June, Moncton, New Brunswick, Canada.

Pan S C, Tseng D H, Lee C C and Lee C. 2003 Influence of fineness of sewage sludge ash on the mortar properties. *Cement and Concrete Research*, 33, 1749-1754.

Perez Carrion M, Baeza-Brotons F, Paya J, Saval J M, Zornoza E, Borrachero M V and Garces P. 2013 Potential use of sewage sludge ash (SSA) as a cement replacement in precast concrete blocks. *Materials de Construccion*, 64, 313.

Takeuchi N, Takahashi H, Ishida S, Takahashi S and Wakamatsu M. 1999 Effect of firing atmosphere on extraordinary expansion of sintered brick from incinerated ash of sewage sludge. *Journal of the Ceramic Society of Japan*, 107(6), 551-554.

Tantawy M A, El-Roudi A M, Abdalla E M and Abdelzaher M A. 2012 Evaluation of the pozzolanic activity of sewage sludge ash. *ISRN chemical engineering*, 2012, 1-8.

Tantawy M A, El-Roudi A M, Abdalla E M and Abdelzaher M A. 2013 Fire resistance of sewage sludge ash blended cement pastes. *Journal of Engineering Hindawi Publishing Corporation*, 2013, 1-7.

Tay J H and Show K Y. 1994 Municipal wastewater sludge as cementitious and blended cement materials. *Cement & Concrete Composites,* 16, 39-48.

Tay J H and Yip W K. 1989 Sludge ash as lightweight concrete material. *Journal of Environmental Engineering*, 115(1), 56-64.

Tseng D H and Pan S C. 2000 Enhancement of pozzolanic activity and morphology of sewage sludge ash by calcinations. *Journal of the Chinese Institute of Environmental Engineering,* 10(4), 261-270.

Wang L, Skjevrak G, Hustad J E and Grønli M G. 2012 Sintering characteristics of sewage sludge ashes at elevated temperatures. *Fuel Processing Technology*, 96, 88-97.

Zhang Z, Zhang L, Yin Y, Liang X and Li A. 2015 The recycling of incinerated sewage sludge ash as a raw material for CaO-Al_2O_3-SiO_2-P_2O_5 glass ceramic production. *Environmental Technology,* 36(9), 1098-1103.

Appendix I: Trace Elements

Adam C, Peplinski B, Michaelis M, Kley G and Simon F G. 2009 Thermochemical treatment of sewage sludge ashes for phosphorus recovery. *Waste Management*, 29, 1122-1128.

Adam C, Suhendra, Vogel C, Krueger O and Tetzlaff K. 2012 Production of marketable multi-nutrient fertilisers from different biomass ashes and industrial by-products. *Proceedings of Ash Utilisation 2012 - Ashes in a Sustainable Society*, Stockholm Sweden, 25-27 January.

Al-Sharif M and Attom M F. 2014 A geoenvironmental application of burned wastewater sludge ash in soil stabilization. *Environmental Earth Sciences*, 71, 2453-2463.

Anderson M and Skerratt R G. 2003 Variability study of incinerated sewage sludge ash in relation to future use in ceramic brick manufacture. *British Ceramic Transactions*, 102(3), 109-113.

Biatowiec A, Janczukowicz W, Gusiatin Z M, Thornton A, Rodziewicz J and Zielinska M. 2014 Recycling potential of air pollution control residue from sewage sludge thermal treatment as artificial lightweight aggregate. *Waste Management & Research*, 32(3), 221-227.

Biswas B K, Inoue K, Harada H, Ohto K and Kawakita H. 2009 Leaching of phosphorus from incinerated sewage sludge ash by means of acid extraction followed by absorption on orange waste gel. *Journal of Environmental Sciences*, 21, 1753-1760.

Cenni R, Janisch B, Spliethoff H and Hein K R G. 2001 Legislative and environmental issues on the use of ash from coal and municipal sewage sludge co-firing as construction material. *Waste Management*, 21, 17-31.

Chang F C, Lin J D, Tsai C C and Wang K S. 2010 Study on cement mortar and concrete made with sewage sludge ash. *Water Science and Technology*, 62(7), 1689-1693.

Chiou I J, Wang K S, Chen C H and Lin Y T. 2006 Lightweight aggregate made from sewage sludge and incinerated ash. *Waste Management*, 26, 1453-1461.

CIRIA. 2004 *Use of sewage sludge in construction*. London: CIRIA C608.

Coutand M, Cyr M and Clastres P. 2006 Use of sewage sludge ash as mineral admixture in mortars. *Construction Materials*, 159, Issue CM4, 153-162.

Damtoft J S, Glavind M, Munch-Petersen C. 2001 Danish Centre for Green Concrete. *Proceedings of CANMET/ACI International Conference,* San Fransisco, September 2001.

Donatello S, Tyrer M and Cheeseman C R. 2010 EU landfill waste acceptance criteria and EU hazardous waste directive compliance testing of incinerated sewage sludge ash. *Waste Management*, 30, 63-71.

Ebbers B, Ottosen L M and Jensen P E. 2015 Comparison of two different electrodialytic cells for separation of phosphorus and heavy metals from sewage sludge ash. *Chemosphere,* 125, 122-129.

Elouear Z, Bouzid J and Boujelben N. 2010 Removal of nickel and cadmium from aqueous solutions by sewage sludge ash: study in single and binary systems. *10th World Wide Workshop for Young Environmental Scientists,* Arcueil, France, 31st May – 4th June.

EU Life. 2007 *Project BioCrete – Chemical Composition of European bio ashes*. EU Life Project. Available from http://www.biocrete.dk/english/20186 [Accessed 5th May 2015].

Fraissler G, Joller M, Mattenberger H, Brunner T and Obernberger I. 2009 Thermodynamic equilibrium calculations concerning the removal of heavy metals from sewage sludge ash by chlorination. *Chemical Engineering and Processing*, 48, 152-164.

Franz M. 2008 Phosphate fertilizer from sewage sludge ash (SSA). *Waste Management*, 28, 1809-1818.

Fraser J L and Lum K R. 1983 Availability of elements of environmental importance in incinerated sludge ash. *Environmental Science & Technology*, 17, 52-54.

Furr K A and Parkinson T F. 1979 Multielement analysis of municipal sewage sludge ashes. Absorption of elements by cabbage grown in sludge ash-soil mixture. *American Chemical Society*, 13(12), 1503-1506.

Fytili D and Zabaniotou A. 2008 Utilization of sewage sludge in EU application of old and new methods – A review. *Renewable and Sustainable Energy Reviews*, 12, 116-140.

Gorazda K, Wzorek Z, Tarko B, Nowak A, Kulczycka J and Henclik A. 2013 Phosphorus cycle - possibilities for its rebuilding. *Acta Biochimica Polonica, 60(4), 725-730.*

Guedes P, Couto N, Ottosen L M and Ribeiro A B. 2014 Phosphorus recovery from sewage sludge ash through an electrodialytic process. *Waste Management*, 34, 886-892.

Gulbrandsen R A, Rait N, Krier D J, Baedecker P A and Childress A. 1978 *Gold, silver and other resources in the ash of incinerated sewage sludge at Palo Alto, California - A preliminary report*. U.S Department of the Interior Geological Survey Circular 784.

Halliday J E. 2008 Properties of sewage sludge ash and its potential use in concrete. In: R DHIR ed. *Role for Concrete in Global Development*, IHS BRE Press, 235-244.

Halliday J E, Dyer T D, Jones M D and Dhir R K. 2012 Potential use of UK sewage sludge ash in cement-based concrete. *Waste and Resource Management Proceedings of the Institute of Civil Engineers*, 165, 57-66.

Havukainen J, Horttanainen M and Linnanen L. 2012 *Feasibility of ASH DEC- process in treating sewage sludge and manure ash in Finland.* Tutkimusraportti Research Report 26. Available from http://www.doria.fi/bitstream/handle/10024/90919/isbn9789252653307.pdf?sequence=2 [Accessed 20/09/15]

Johnson C A. 2003 Characterisation and leachability of sewage sludge ash. In eds. Dhir R K, Newlands M D and Dyer T D Sustainable Waste Management: *Proceedings of the International Symposium held at University of Dundee, UK*, 9-11 September, p353.

Kakumazaki J, Kato T and Sugawara K. 2014 Recovery of gold from incinerated sewage sludge ash by chlorination. *ACS Sustainable Chemistry & Engineering*, 2, 2297-2300.

Khanbilvardi R and Afshari-Tork S. 1995 Sludge ash as fine aggregate for concrete mix. *Journal of Environmental Engineering*, 121(9), 633-638.

Koisor-Kazberuk M. 2011 Application of SSA as partial replacement of aggregate in concrete. *Polish Journal of Environmental Studies*, 20(2), 365-370.

Kruger O, Grabner A and Adam C. 2014 Complete survey of German sewage sludge ash. *Environmental Science & Technology*, 48, 11811-11818.

Lapa N, Barbosa R, Lopes M H, Mendes B, Abelha P, Gulyurtlu I and Oliveira J S. 2007 Chemical and ecotoxicological characterization of ashes obtained from sewage sludge combustion in a fluidised-bed reactor. *Journal of Hazardous Materials*, 147, 175-183.

Latosinska J. 2014 The evaluation of the impact of sewage sludge ash modification on leaching of heavy metals. *Advances in Civil and Environmental Engineering*, 1(1), 27-42.

Li R, Zhao W, Li Y, Wang W and Zhu X. 2015 Heavy metal removal and speciation transformation through the calcinations treatment of phosphorus-enriched sewage sludge ash. *Journal of Hazardous Materials*, 283, 423-431.

Lin K L and Lin C Y. 2004 Hydration properties of eco-cement pastes from waste sludge ash clinkers. *Journal of the Air & Waste Management Association*, 54(12), 1534-1542.

Lin K L and Lin C Y. 2005 Hydration characteristics of waste sludge ash utilized as raw cement material. *Cement and Concrete Research*, 35, 1999-2007.

Lin K L and Lin C Y. 2006 Feasibility of using ash from sludge incineration as raw material for eco-cement. *Journal of the Chinese Institute of Environmental Engineering*, 16(1), 39-46.

Lin D F, Luo H L and Sheen Y N. 2005 Glazed tiles manufactured from incinerated sludge ash and clay. *Journal of the Air and Waste Management Association*, 55(2), 163-172.

Lin K L, Chiang K Y and Lin C Y. 2005 Hydration characteristics of waste sludge ash that is reused in eco-cement clinkers. *Cement and Concrete Research*, 35, 1074-1081.

Lin D F, Luo H L, Hsiao D H and Yang C C. 2005 The effects of sludge ash on the strength of soft subgrade soil. *Journal of the Chinese Institute of Environmental Engineering*, 15(1), 1-10.

Lin K L. Huang W J, Chen K C and Chow J D. 2009 Behaviour of heavy metals immobilized by co-melting treatment of sewage sludge ash and municipal solid waste incinerator fly ash. *Waste Management & Research*, 27, 660-667.

Mattenberger H, Fraissler G, Brunner T, Herk P, Hermann L and Obernberger I. 2008 Sewage sludge ash to phosphorus fertiliser: Variables influencing heavy metal removal during thermochemical treatment. *Waste Management*, 28, 2709-2722.

Mattenberger H, Fraissler G, Jöller M, Brunner T, Obernberger I, Herk P and Hermann L. 2010 Sewage sludge ash to phosphorus fertiliser (II): Influences of ash and granulate type on heavy metal removal. *Waste Management*, 30, 1622-1633.

Morais L C, Dweck J, Goncalves E M and Buchler P M. 2005 An experimental study of sewage sludge incineration. *Environmental Technology*, 27(9), 1047-1051.

Morais L C, Dweck J, Valenzuela F R, Goncalves E M and Buchler P M. 2006 *Characterization of sludge after thermal treatment*. Available from https://www.ipen.br/biblioteca/cd/ptech/2005/PDF/22_14.PDF [Accessed 20/05/15]

Morais L C, Dweck J, Campos V and Buchler P M. 2009 Characterization of sewage sludge ashes to be used as a ceramic raw material. *Chemical Engineering Transactions*, 17, 1813-1818.

NCHRP. 2013 *Recycled Materials and Byproducts in Highway Applications,* Volume 3: Non-coal combustion byproducts, Synthesis 435.

Nowak B, Perutka L, Aschenbrenner P, Kraus P, Rechberger H and Winter F. 2011 Limitations for heavy metal release during thermo-chemical treatment of sewage sludge ash. *Waste Management*, 31, 1285-1291.

Nowak B, Wegerer H, Aschenbrenner P, Rechberger H and Winter F. 2012 Sewage sludge ash to phosphate fertilizer by chlorination and thermal treatment: residence time requirements for heavy metal removal. *Environmental Technology,* 33(21), 2375-2381.

Ohbuchi A, Sakamoto J, Kitano M and Nakamura T. 2008 X-ray fluorescence analysis of sludge ash from sewage disposal plant. *X-Ray Spectrometry*, 37, 544-550.

Ottosen L M, Kirkelund G M and Jensen P E. 2013 Extracting phosphorus from incinerated sewage sludge ash rich in iron or aluminium. *Chemosphere*, 91, 963-969.

Ottosen L M, Jensen P E and Kirkelund M. 2014 Electrodialytic separation of phosphorus and heavy metals from two types of sewage sludge ash. *Separation Science and Technology,* 49(12), 1910-1920.

Paramasivam S, Sajwan K S and Alva A K. 2005 Incinerated sewage sludge products as amendments for agricultural soils: leaching and plant uptake of trace elements. *Water, Air and Pollution*, 171, 273-290.

Peplinski B, Adam C, Reuther H, Vogel C, Adamczyk B, Menzel M, Emmerling F and Simon F G. 2011 First identification of the tridymite form of $AlPO_4$ in municipal sewage sludge ash. *Z. Kristallogr. Proceedings*, 1, 443-448.

Peplinski B, Adam C, Adamczyk B, Muller R, Schadrack R, Michaelis M, Emmerling F, Reuther H and Menzel M. 2013 Evidence of formation of the tridymite form of $AlPO_4$ in some municipal sewage sludge ashes. *Powder Diffraction*, 28(S2), S425-S435.

Peplinski B, Adam C, Adamczyk B, Muller R, Michaelis M, Krahl T and Emmerling F. 2014 Nanocrystalline and stacking-disordered B-cristobalite $AIPO_4$: the now deciphered main constituent of a municipal sewage sludge ash from a full-scale incineration facility. *Powder Diffraction*, 30, S31-S35.

Rapf M, Raupenstrauch H, Cimatoribus C and Kranert M. 2012 *A new thermo-chemical approach for the recovery of phosphorus from sewage sludge*. European Commission CORDIS Project. Available from http://www.vivis.de/phocadownload/2012_wm/2012_WM_691_698_Rapf.pdf [Accessed 10 May 2015]

Saikia N, Kato S and Kojima T. 2006 Compositions and leaching behaviours of combustion residues. *Fuel*, 85, 264-271.

Schaum C, Cornel P and Jardin N. 2011 *Phosphorus recovery from sewage sludge ash – a wet chemical approach*, Technische Universität Darmstadt, Germany. Available from

http://www.bvsde.paho.org/bvsaar/cdlodos/pdf/phosphorusrecovery583.pdf [Accessed 17 May 2013].

Takaoka M, Yamamoto T, Fujiwara S, Oshita K, Takeda N, Tanaka T, Uruga T. 2008 Chemical States of Trace Heavy Metal in Sewage Sludge Incineration Ash by using X-ray absorption fine structure. *Water Science & Technology*, 57(3), 411-417.

Tateda M, Ike M and Fujita M. 1997 Loss of metallic elements associated with ash disposal and social impacts. *Resources, Conservation and Recycling*, 19, 93-108.

Tay J H and Show K Y. 1992 Utilization of municipal wastewater sludge as building and construction materials. *Resources, Conservation and Recycling*, 6, 191-204.

Tay J H and Show K Y. 1997 Resource recovery of sludge as a building and construction material – A future trend in sludge management. *Water Science and Technology*, 36(11), 259-266.

Tempest B Q and Pando M A. 2013 Characterization and demonstration of reuse applications of sewage sludge ash. *International Journal of Geomatics and Geosciences*, 4(2), 552-559.

Tsai C C, Wang K S and Chiou I J. 2006 Effect of SiO_2 – Al_2O_3 – flux ratio change on the bloating characteristics of lightweight aggregate material produced from recycled sewage sludge. *Journal of Hazardous Materials*, B134, 87-93.

USEPA. 1972 *Sewage sludge incineration.* Report no. EPA-R2-72-040, PB 211 323.

Vogel C and Adam C. 2011 Heavy metal removal from sewage sludge ash by thermochemical treatment with gaseous hydrochloric acid. *Environmental Science & Technology*, 45, 7445-7450.

Vogel C, Exner R M and Adam C. 2013 Heavy Metal Removal from Sewage Sludge Ash by Thermochemical Treatment with Polyvinylchloride. *Environmental Science and Technology*, 47, 563-567.

Vogel C, Adam C, Kappen P, Schiller T, Lipiec E and Mcnaughton D. 2014 Chemical state of chromium in sewage sludge ash based phosphorus fertilisers. *Chemosphere*, 103, 250-255.

Xu H, He P, Gu W, Wang G and Shao L. 2012 Recovery of phosphorus as struvite from sewage sludge ash. *Journal of Environmental Sciences*, 24(8), 1533-1538.

Zhang F S, Yamasaki S and Nanzyo M. 2002 Waste ashes for use in agricultural production: I. Liming effect, contents of plant nutrients and chemical characteristics of some metals. *The Science of the Total Environment*, 284, 215-225.

Zhang F S. Yamasaki S and Kimura K. 2002 Waste ashes for use in agricultural production: II. Contents of minor and trace elements. *The Science of the Total Environment*, 286, 111-118.

Zhang Z, Li A, Yin Y and Zhao L. 2013 Effect of crystallization time on behaviours of glass-ceramic produced from sludge incineration ash. *Procedia Environmental Sciences*, 18, 788-793.

Zhang Z, Zhang L, Yin Y, Liang X and Li A. 2015 The recycling of incinerated sewage sludge ash as a raw material for CaO-Al_2O_3-SiO_2-P_2O_5 glass ceramic production. *Environmental Technology*, 36(9), 1098-1103.