

SLUDGE-DERIVED SLAG GENERATED FROM HIGH TEMPERATURE SLAGGING CO-GASIFICATION OF SLUDGE AND WASTES IN SUSTAINABLE CONCRETE PRODUCTION

5 Field of Invention

The current invention relates to a particulate slag suitable for use to replace sand or fine aggregates in a concrete, a method of providing the particulate slag suitable for use to replace sand or fine aggregates in a concrete, a mortar comprising the particulate slag, and a concrete
10 comprising the particulate slag.

Background

The listing or discussion of a prior-published document in this specification should not
15 necessarily be taken as an acknowledgement that the document is part of the state of the art or is common general knowledge.

Waste reduction and reuse have emerged as the most favoured approaches in waste management. However, in tandem with positive strides, challenges continue to arise in various
20 facets of waste management. Wastewater treatment facilities are generating significant amount of sewage sludge (exceeds 100 million tonnes sewage sludge worldwide per year) that necessitate appropriate treatment or disposal (Venkatesan, A.K. et al., *Environmental Science and Pollution Research*, **2015**, 22, 1577; Escala, M. et al., *Energy & Fuels*, **2013**, 27, 454; Kelessidis, A. & Stasinakis, A. S., *Waste Management*, **2012**, 32, 1186). Besides the high
25 moisture content, sewage sludge is composed of organic substances, microorganisms, extracellular polymeric substances, minerals, and metals (Anumol, T. & Snyder S. A., *Talanta*, **2015**, 132, 77; Zheng, M. et al., *J. Hazard. Mater.*, **2021**, 402, 123484), potentially valuable for energy and materials recovery.

30 Techniques currently applicable for sewage sludge treatment include landfilling, agricultural usage, anaerobic digestion, incineration, pyrolysis, and gasification (Raheem, A. *Chem. Eng. J.*, **2018**, 337, 616). Among those techniques, landfilling, agricultural usage, anaerobic digestion, and incineration are the prevailing methods applied (Hao, X. et al., *Water Res.*, **2020**, 170, 115298; Liang, Y. et al., *J. Clean. Prod.*, **2021**, 295). However, the contaminants
35 in sewage sludge such as heavy metals and hazardous organic substances can present risks to the environment even if the sewage sludge can provide phosphorus and nitrogen resources to the soil. Incineration reduces the amount of sewage sludge by ~90% in volume and ~70%

in weight, while completely destructing pathogens and organic pollutants (Raheem, A. *Chem. Eng. J.*, **2018**, 337, 616; Krüger, O. et al., *Environ. Sci. Tech.*, **2014**, 48, 11811). Nevertheless, the incineration solid ash residues, mainly incineration bottom ash (IBA) and incineration fly ash (IFA, after flue gas treatment process), are considered to be hazardous and cannot be readily reused. The ashes usually are disposed to landfills (Lin, W.Y. et al., *J. Hazard. Mater.*, **2018**, 357, 63). On the other hand, landfilling requires large land area, posing significant burden to sustainable urban development (Hao, X. et al., *Water Res.*, **2020**, 170, 115298). Agricultural usage of sludge is highly restricted due to relatively low nutritional values as compared to conventional fertilizers and the presence of heavy metals. Anaerobic digestion recovers valuable resources from sewage sludge such as biogas while reducing the mass and volume of sludge (Cao, Y. Pawlowski, A. *Renew. Sustain. Energy Rev.*, **2012**, 16, 1657; Devlin, D.C. et al., *Bioresour. Technol.*, **2011**, 102, 4076). However, low carbon conversion efficiency, potentially unstable biogas quality and the generation of digested sludge as residue which requires further treatment or disposal lead to the needs for the development and application of alternative technologies (Raheem, A. *Chem. Eng. J.*, **2018**, 337, 616). Pyrolysis is another technique for sewage sludge treatment, with separated products in three different phases: pyrolytic gas, bio-oil, and solid char, which are potentially valuable resources (Du, Z. et al., *J. Hazard. Mater.*, **2022**, 424, 127346; Tian, Y.U. et al., *Environ. Sci. Tech.*, **2013**, 47, 3498). Yet pyrolysis of sewage sludge is at a relatively early stage of development of engineering solutions for the technical challenges observed including high energy consumption, proper control and stabilization of heavy metal pollutants, and process compatibility with different types of sludge (Raheem, A. *Chem. Eng. J.*, **2018**, 337, 616).

The constraints of landfill capacity, rising expenses associated with waste disposal in incineration facilities and landfills, depletion of natural resources, and the imperative for sustainable development have all heightened the urgency to repurpose materials that were previously considered waste as viable alternatives to natural resources (Lim, T.-T. & Chu, J., *Waste Management & Research*, **2006**, 24, 67).

As an advanced waste-to-energy (WTE) treatment method, gasification converts wastes into gaseous fuel (syngas) to be considered an effective and environmentally friendly technology (Chan, W.P. et al., *Applied Energy*, **2019**, 237, 227; Yang, S. et al., *Energy Conversion and Management*, **2020**, 223, 113439). Among various gasification techniques, the high-temperature slagging gasification (HTSG) is considered as one of the most promising options for sewage sludge treatment which employed a direct melting furnace system. High temperature slagging gasification is a unique type of gasification that employ very high temperature (>1600 °C) and oxygen enriched air to convert different types of wastes into

usable slag (Yang, C.H.J.K. et al., *Chemical Engineering Journal*, **2023**, 465, 142874; Roche, E. et al., *Fuel*, **2014**, 115, 54; Raheem, A. *Chem. Eng. J.*, **2018**, 337, 616). The gasification conditions, the use of additives for the melting of inorganic residues, the properties and composition of the slag, and the stabilities of metals in the slag vary with the input of different types of waste materials. Considering the high moisture and ash contents present in sludge (Anumol, T. & Snyder S. A., *Talanta*, **2015**, 132, 77; Zheng, M. et al., *J. Hazard. Mater.*, **2021**, 402, 123484), which can negatively impact process efficiency, a synergistic approach can be adopted by co-gasifying the sludge with other waste residues (Ong, Z. et al., *AIChE Journal*, **2015**, 61, 2508). Co-gasification of municipal solid waste (MSW) with sewage sludge, waterworks sludge, and sludge incineration ash can convert diverse waste streams into slag while recover the energy from the wastes (Peng, L. et al., *Bioresource Technology*, **2012**, 114, 698; Heberlein, S. et al., *Journal of Hazardous Materials*, **2022**, 423, 127057).

The slagging gasification process operates at over 1500 °C and the combustible components will be gasified at high temperature, which allows the destruction of complex hydrocarbons during the slagging gasification process, while the ash, the non-combustibles materials are melted and transformed into vitrified slag, a glass-like alternative to the bottom ash from incineration (Raheem, A. *Chem. Eng. J.*, **2018**, 337, 616), and metals (Akashi, T. & Sudo, M., *JFE Technical Report*, **2009**, 13, 67; Matsudaira, T. et al., *JFE Technical Report*, **2004**, 15; Katafuchi, M. et al., *Waste Management*, **2015**, 5, 453). The slag then can be separated from recyclable metals by magnetic separator. Granular metals particles can be separated from the mixes of slag generated (cooled with water quenching system at the exit of the gasifier) to form a separate product stream as recyclable metals. The metals are further recovered by refinery factories for extracting valuable metals. Silicon dioxide (SiO₂), aluminium oxide (Al₂O₃), calcium oxide (CaO), and magnesium oxide (MgO) are the major constituents in the slag, while the trace heavy metals are in stabilized forms (Wang, X. et al., *Journal of Material Cycles and Waste Management*, **2017**, 19, 483; Ferraris, M. et al., *Waste Management*, **2009**, 29, 1041). The vitrification of inorganic solid residues during the formation of slag can contribute towards stabilization of heavy metals which may allow the slag generated to be reused while the incineration ashes can only be landfilled (Moustakas, K. et al., *J. Hazard. Mater.*, **2012**, 207-208, 44; Sanito, R.C. et al., *J. Environ. Manage.*, **2022**, 316, 115243). The desirable mechanical properties and low leaching potential of heavy metals from the slag suggest that it is potentially an attractive alternative aggregate for the replacement of natural resources such as sand for construction (Moustakas, K. et al., *J. Hazard. Mater.*, **2012**, 207-208, 44; Saffiudin, M. et al., *International Journal of the Physical Sciences*, **2010**, 5, 1952; Tanigaki, N. et al., *Waste Management*, **2015**, 37, 137). The remaining slag with glass-like, inert, and mechanical properties is considered as commercially reusable by-product (Roessler, J.G. et

al., *Waste Management*, **2016**, 52, 169) and can potentially be reused as a construction material (Amran, M. et al., *Constr. Build. Mater.*, **2021**, 272, 121942). The reutilisation of slag as a waste-derived construction material could reduce the environmental impacts due to excavation, transportation and utilization of sands. HTSG is therefore considered to be more effective in waste volume and mass reductions as compared to conventional incineration technologies (Heberlein, S. et al., *Journal of Hazardous Materials*, **2022**, 423, 127057).

Similarly, waterworks sludge (WWS) is another concern and burden to the landfills worldwide. Alum and ferric salts are the commonly used coagulants in water purification process, and they are the main sources for WWS. Generated from the respective coagulants, the sludge is either called Alum sludge or Ferric sludge (Zhao, Y. et al., *Waste Biomass Valoriz.*, **2020**, 12, 4239). Currently, the WWS is treated through dewatering process and then either direct landfilled or incinerated into ashes for landfill (Zhao, Y. et al., *Waste Biomass Valoriz.*, **2020**, 12, 4239; Ahmad, T. et al., *J. Clean. Prod.*, **2016**, 124, 1). Since WWS contains high mineral contents and less organic (or combustible) contents, it is either considered as non-combustible waste, or would generate a higher ratio of ashes during incineration. Thus, HTSG could potentially be an effective method to treat WWS as high abundance of minerals favours the generation of slag while co-gasification process provides sufficient energy for melting and co-treatment.

Coal slag, steel slag, copper slag, and MSW slag are the common by-products generated from various industrial processes and waste treatment which could be promising for reuse. The main composition of the coal gasification slag was found to be SiO_2 (47.78 wt.%) (Fu, B. et al., *Construction and Building Materials*, **2022**, 323, 126587). The specimen with 10% cement substitute by coal gasification slag has a positive effect on the compressive strength for 1, 7, and 28 days compared to 100% cement pastes. However, the compressive strengths of all cement pastes decrease with the further increasing the amount of gasification slag, especially for the coal gasification slag content higher than 50%. Moreover, the initial and final setting times increase significantly when the coal gasification slag content was higher than 10% (Fu, B. et al., *Construction and Building Materials*, **2022**, 323, 126587). The heavy metal pollution exists in coal gasification slag as the elemental concentration of chromium (Cr), manganese (Mn), nickel (Ni), etc. exceeded the U.S. standard (TCLP, U.S. EPA method 1311) and Chinese standard (GB/T 14848-2017) (Guo, Y. et al., *Separation and Purification Technology*, **2023**, 306, 122675). The steel slag, which produced during the separation of the molten steel from impurities in steel-making furnaces, primarily consists of CaO (40.2 ± 8.7 wt.%), $\text{FeO/Fe}_2\text{O}_3$ (19.8 ± 10.9 wt.%), SiO_2 (16.3 ± 4.8 wt.%), MgO (6.3 ± 3.1 wt.%), Al_2O_3 (5.3 ± 3.6 wt.%) with a density of $3.3 - 3.6 \text{ g/cm}^3$ (Gencel, O. et al., *Construction and Building*

Materials, **2021**, 283, 122783). Fatal volume expansion and heavy metal leaching (including Ba, Cr, Pb, and V ions) are encountered in the application of steel slag in civil engineering (Pan, S.-Y. et al., *Journal of Cleaner Production*, **2018**, 196, 1266). Therefore, pre-treatment on steel slag is necessary for potential utilisation of the steel slag. The copper slag, a by-product of copper extraction by smelting, shows a high Fe_2O_3 content (36 - 62 wt.%) with a high density of 3.16 - 3.87 g/cm^3 as well (Al-Jabri, K.S. et al., *Construction and Building Materials*, **2011**, 25, 933; Shi, C. et al., *Conservation and Recycling*, **2008**, 52, 1115). The other chemical compositions include SiO_2 (24.7 - 40.97 wt.%), CaO (0.6 - 10.9 wt.%), MgO (0.75- 2.82 wt.%), Al_2O_3 (2.4 - 15.6 wt.%), CuO (0.33 - 2.1 wt.%), etc. (Shi, C. et al., *Conservation and Recycling*, **2008**, 52, 1115). The copper slag needs appropriate treatment or washing to meet certain recycling standards prior to its potential utilization in different applications (B.a.C. Authority, SUSTAINABLE CONSTRUCTION – A Guide on the Use of Recycled Materials, BCA Academy of the Built Environment, 2008). MSW slag from high-temperature arc gasification (HTAG) of MSW mainly consists of SiO_2 (30.8 wt.%), Al_2O_3 (22.6 wt.%), CaO (22.0 wt.%), MgO (12.3 wt.%) (Blaisi, N.I. et al., *Journal of Cleaner Production*, **2018**, 196, 1266). MgO has been reported to play a substantial role in delaying hydration heat evolution and the high MgO content could result in aggregate expansion due to hydration (Roessler, J.G. et al., *Waste Management*, **2016**, 52, 169; Blaisi, N.I. et al., *Journal of Cleaner Production*, **2018**, 196, 1266). Additionally, the compressive strength test on 7, 28, and 56 days show the modest substitution levels (5%) of Portland cement with MSW slag yield comparable strength. However, notable reductions in strength and heat generation are observed with greater substitution levels (20 - 50%) (Blaisi, N.I. et al., *Journal of Cleaner Production*, **2018**, 196, 1266).

Nevertheless, the HTSG is usually applied for the treatment biomass and MSW only. Research efforts have been dedicated to investigating the reutilization of different types of waste-derived slags, but a limited understanding of the co-gasification slag derived from sludge and mixture of wastes and the reuse of the slag has been addressed. The concurrent co-gasification of various of waste materials, including MSW with sewage sludge, waterworks sludge, and sludge incineration ash, is not generally applied at large scale while for the few co-gasification facilities that co-gasify the sludge and ash in the direct melting furnace, the co-feeding is maintained at relatively low co-gasification ratio of less than 20% (about 10–15% of sludge) (Shibaike, H. et al., Development of High-Performance Direct Melting Process for Municipal Solid Waste, *Nippon Steel Technical Report*, 2005; Tanigaki, N. *Pyrolysis/Gasification*, **2017**, 379). This is because the gasification conditions, the use of additives for the melting of inorganic residues, the properties and composition of the slag, and the stabilities of metals in the slag vary with the input of different types of waste materials. The

co-gasification of significant amount of sludge could contribute to the changes in the composition and properties of the slag generated. Therefore, the generation and subsequent application of sludge-derived slag require further development based on comprehensive technical and environmental assessments. It is important to explore and demonstrate the potential of HTSG to be applied as an alternative treatment method for different types of sludge and ash residues at higher loading rate and co-gasification ratio.

Summary of Invention

Co-gasification of sludge/ash and MSW reduces the amount of waste and produces energy while generates slag originate from the non-combustible residues in sludge and MSW. It has been surprisingly found a sludge-derived slag formed from the co-gasification MSW with one or more of wastewater sludge, a freshwater sludge and a sludge incineration ash can be used to replace sand in mortars and concretes.

Aspects and embodiments of the invention will now be discussed by reference to the following numbered clauses.

1. A method of providing a particulate slag suitable for use to replace sand or fine aggregates in a concrete, the method comprising the steps of:

(a) feeding a municipal solid waste and one or more of a wastewater sludge, a freshwater sludge and a sludge incineration ash through a top portion of a gasifier; and

(b) collecting a molten slag formed from the municipal solid waste and one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash from a slag collection outlet of the gasifier, quenching the molten slag to form granules and removing at least some diamagnetic metal particles from the slag to provide a slag suitable for using to replace sand or fine aggregates in a concrete, wherein:

the weight to weight ratio of the municipal solid waste to one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash is from 10:1 to 1:2; and

a bottom section of the gasifier is operated at a temperature of from 1,200 to 2,500 °C.

2. The method according to Clause 1, wherein the temperature of the bottom section of the gasifier is from 1,300 to 2,200 °C, such as from 1,500 to 2,000 °C, such as about 1,600 °C.

3. The method according to Clause 1 or Clause 2, wherein the weight to weight ratio of the municipal solid waste to one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash is from 9:1 to 1:1, such as 3.17:1 to 2:1.

4. The method according to any one of the preceding clauses, wherein the wastewater sludge, the freshwater sludge and the sludge incineration ash is selected from one or more of the group consisting of a dewatered alum sludge, a dried sludge from a wastewater treatment facility, bottom ash particles formed from incineration of a sludge, and sludge incineration fine ash particles.

5. The method according to any one of the preceding clauses, wherein the loading rate for the municipal solid waste is from 200 to 500 ± 110 kg/h, such as from 222 to 428 ± 108 kg/h and the loading rate of the one or more of the wastewater sludge, freshwater sludge and the sludge incineration ash may be commensurate with the weight:weight ratios described in Clause 1 or Clause 3.

6. The method according to any one of the preceding clauses, wherein the total loading rate for one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash is from 40 to 250 ± 60 kg/h, such as from 42 to 217 ± 60 kg/h and the loading rate of the municipal solid waste is commensurate with the weight:weight ratios described in Clause 1 or Clause 3.

7. The method according to any one of the preceding clauses, wherein the apparatus used in the method further comprises a combustion chamber, a boiler, a cyclone, a gas cooling tower and a bag filter, which are fluidly linked in series in order to process a syngas produced by feeding both of the municipal solid waste and one or both of the wastewater sludge and a sludge incineration ash into the gasifier.

8. A particulate slag suitable for use to replace sand or fine aggregates in a concrete, the slag's elemental composition comprising each of Ca, Si, Al, Na, Fe, Mg, P, K, Ti, and Mn in an amount greater than 1g/kg.

9. The particulate slag according to Clause 8, wherein the slag has one or more properties selected from:

- (i) a mean particle size diameter that is less than 40 mm, optionally wherein the mean particle size diameter is from 1 to 5 mm, such as from 2.0 to 3.1 mm;
- (ii) the water absorption of the slag is from 0.5 to 0.7%, such as about 0.64%;

- (iii) the specific gravity of the slag is from 2.6 to 2.9, such as from 2.72 to 2.8;
- (iv) the bulk density of the slag is from 1.2 to 1.6 g/cm³, such as from 1.31 to 1.51 g/cm³;
- (v) the particle density of the slag on an oven-dried basis is from 2.5 to 3.0 g/cm³, such as from 2.74 to 2.80 g/cm³.

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10. The particulate slag according to Clause 9, wherein the slag has all of the properties listed in (i) to (v) of Clause 9.

10 11. The particulate slag according to any one of Clauses 8 to 10, wherein the particulate slag has angular to sub-angular morphology.

12. The particulate slag according to any one of Clauses 8 to 11, wherein the particulate slag is in an amorphous solid form.

15 13. A mortar comprising:

a particulate slag according to any one of Clauses 8 to 12, or a particulate slag obtainable from a method according to any one of Clauses 1 to 7; and
a cement.

20 14. A concrete comprising:

a particulate slag according to any one of Clauses 8 to 12, or a particulate slag obtainable from a method according to any one of Clauses 1 to 7;

a cement;

an admixture; and

25 coarse aggregates.

15. The concrete according to Clause 14, wherein the concrete has one or more of the following properties:

(ia) a water absorption of from 1.85 to 2.00%;

30 (ib) a resistance to chloride ingress, once cured, of from 1379 to 1877 coulombs;

(ic) a compressive strength comparable to a concrete of Clause 14 made using sand instead of the particulate slag.

35 A set of well-engineered and predictable concrete products produced of co-gasification sludge-derived slag with the properties of:

- a. Low environmental impact green concrete (eliminates the need for excavation of natural sand).
- b. Low water absorption (1.85 to 2.00%).
- c. High resistance to chloride ingress (1379 to 1877 coulombs with grading identified as low) and good durability.
- d. Comparable compressive strength to typical sand concrete and potentially applicable for both non-structural and structural applications.

Drawings

FIG. 1 depicts the schematic layout of Waste-to-Energy Research Facility (WTERF) on co-gasification process.

FIG. 2 depicts samples of (a) dewatered alum waterworks sludge (AI-WWS) slag, (b) dried municipal sewage sludges derived slag (DS slag), (c) sludge incineration bottom ash derived slag (BA slag), and (d) mix of sludge incineration fine ashes and dewatered sludge derived slag (MA+M-DWS slag).

FIG. 3 depicts the photos of the samples: (a) AI-WWS, (b) DS, (c) BA, and (d) MA+M-DWS mixtures.

FIG. 4 depicts the particle size distribution of various sludge-derived slag.

FIG. 5 depicts the pictures and stereomicroscope images of (a) AI-WWS slag, (b) DS slag, (c) BA slag, (d) MA+M-DWS slag.

FIG. 6 depicts the photomicrograph of mineral constituent of Slag and Opaque Mineral fragments for (a) AI-WWS slag, (b) DS slag, (c) BA slag, and (d) MA+M-DWS slag.

FIG. 7 depicts the XRD diffractogram of the river sand, cement, and various sludge-derived slag.

FIG. 8 depicts the compressive strength of various sludge-derived slag mortars.

FIG. 9 depicts the XRD diffractogram of various slag mortars.

FIG. 10 depicts the consolidation coefficient of various sludge-derived slag.

FIG. 11 depicts the boundary conditions for (a) sand concrete and (b) slag concrete with a functional unit of 1000 kg concrete.

- 5 FIG. 12 depicts the boundary conditions for (a) reclamation by sand and (b) reclamation by slag with a functional unit of 1 m³ land reclamation.

FIG. 13 depicts (a) global warming potential (GWP), (b) acidification potential (AP), (c) eutrophication potential (EP), (d) human toxicity potential (HTP), and (e) marine aquatic
10 ecotoxicity potential (MAETP) of sand concrete and slag concrete.

Description

The current invention relates to the formation of a sludge-derived slag (e.g. a glass-like sludge-
15 derived slag) from the high temperature co-gasification of a MSW with at least one other wastewater waste. This material is surpassingly useful as a construction material that can be used to replace sand. As such, the resulting material may reduce the environmental impact and cost for the fabrication of mortars and concrete construction materials due to the low-cost of the raw material and the ability to generate the slag locally from waste materials with no
20 need for a special utilization facility. As such, the current invention may save natural resources, such as natural sand. In addition, the current invention may reduce the needs for waste disposal at landfill through making use of sludge-derived slag for producing commercially usable construction materials. As discussed herein, sludge-derived slag can be used to replace river sand as fine aggregate in concrete production.

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Thus, in a first aspect of the invention, there is provided a method of providing a particulate slag suitable for use to replace sand or fine aggregates in a concrete, the method comprising the steps of:

- (a) feeding a municipal solid waste and one or more of a wastewater sludge, a freshwater
30 sludge and a sludge incineration ash through a top portion of a gasifier; and
(b) collecting a molten slag formed from the municipal solid waste and one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash from a slag collection outlet of the gasifier, quenching the molten slag to form granules and removing at least some diamagnetic metal particles from the slag to provide a slag suitable for using to
35 replace sand or fine aggregates in a concrete, wherein:

the weight to weight ratio of the municipal solid waste to one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash is from 10:1 to 1:2; and

a bottom section of the gasifier is operated at a temperature of from 1,200 to 2,500 °C.

The word “comprising” refers herein may be interpreted as requiring the features mentioned, but not limiting the presence of other features. Alternatively, the word “comprising” may also relate to the situation where only the components/features listed are intended to be present (e.g. the word “comprising” may be replaced by the phrases “consists of” or “consists essentially of”). It is explicitly contemplated that both the broader and narrower interpretations can be applied to all aspects and embodiments of the present invention. In other words, the word “comprising” and synonyms thereof may be replaced by the phrase “consisting of” or the phrase “consists essentially of” or synonyms thereof and *vice versa*.

The phrase, “consists essentially of” and its pseudonyms may be interpreted herein to refer to a material where minor impurities may be present. For example, the material may be greater than or equal to 90% pure, such as greater than 95% pure, such as greater than 97% pure, such as greater than 99% pure, such as greater than 99.9% pure, such as greater than 99.99% pure, such as greater than 99.999% pure, such as 100% pure.

As used herein, the singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a composition” includes mixtures of two or more such compositions, and the like.

As noted herein, the particulate slag suitable for use to replace sand or fine aggregates in a concrete, but it may be used for other purposes too. For example, the particulate slag may also be used to replace sand or fine aggregates in a mortar, as discussed below.

The term “municipal solid waste” or MSW may refer to trash or garbage in the United States and rubbish in Britain. As such, it is a waste type consisting of everyday items that are discarded by the public. In the European Union, the semantic definition is 'mixed municipal waste,' given waste code 20 03 01 in the European Waste Catalogue.

The term “wastewater sludge” may be used herein to refer to a sludge generated by the treatment of a wastewater. As such, it may refer to a residual, semi-solid material that is produced as a by-product during treatment of industrial or municipal wastewater.

The term “freshwater sludge” may be used herein to refer to a sludge generated by the treatment of freshwater (e.g. from a source of fresh water, such as a river, a lake or rain water).

As such, it may refer to a residual, semi-solid material that is produced as a by-product during treatment of a fresh water.

5 The term “sludge incineration ash” may refer to the ash generated by the incineration of sludge, for example a wastewater sludge or a freshwater sludge.

As noted herein, MSW and one or more of a wastewater sludge, a freshwater sludge and a sludge incineration ash are subjected to co-gasification in a gasifier. In the first instance, these waste materials may be supplied to a top portion of a gasifier and a resulting molten slag may
10 be collected at a collection outlet of the gasifier. This outlet will generally be in a bottom portion of the gasifier. The resulting molten slag is then subjected to quenching the molten slag to form granules and removing at least some diamagnetic metal particles from the slag to provide a slag suitable for using to replace sand or fine aggregates in a concrete. As will be appreciated “diamagnetic metal particles” refer to metal particles that freely magnetise when
15 placed in a magnetic field and so may become attracted to the magnets used, thereby allowing these particles to be removed from the resulting slag.

It will also be appreciated that the gasifier will not only produce the molten slag, but may also produce a syngas. This syngas may then be subjected to further processing by a system
20 designed to deal with such a fluid. As such, the apparatus used in the above method may further comprise a combustion chamber, a boiler, a cyclone, a gas cooling tower and a bag filter, which are fluidly linked in series in order to process a syngas produced by feeding both of the municipal solid waste and one or both of the wastewater sludge and a sludge incineration ash into the gasifier.

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As noted herein, a bottom section of the gasifier is operated at a temperature of from 1,200 to 2,500 °C. This bottom section is intended to be where the molten slag is collected and subjected to the further steps needed to provide the desired particulate slag suitable for use to replace sand or fine aggregates in a concrete. Any suitable temperature within this
30 temperature range may be used. For example, the temperature of the bottom section of the gasifier may be from 1,300 to 2,200 °C, such as from 1,500 to 2,000 °C, such as about 1,600 °C.

As noted herein, the weight to weight ratio of the municipal solid waste to one or both of the
35 wastewater sludge and the sludge incineration ash is from 10:1 to 1:2. Any suitable weight to weight ratio within this region may be used. For example, the weight to weight ratio of the municipal solid waste to one or more of the wastewater sludge, the freshwater sludge and the

sludge incineration ash may be from 9:1 to 1:1, such as 3.17:1 to 2:1. As will be appreciated, when there is more than one of the wastewater sludge, freshwater sludge and the sludge incineration ash then the weight to weight ratio is based on the weight of the MSW relative to the total weight of the wastewater sludge, freshwater sludge and the sludge incineration ash used. For the avoidance of doubt, the terms “wastewater sludge”, “freshwater sludge” and “sludge incineration ash” may refer to one or more (e.g. 2, 3, or 4 of that type of material, which may then be used alone (as a combination of that type of material) or in combination with the other types of materials).

Any suitable wastewater sludge, freshwater sludge and sludge incineration ash may be used alone or in combination along with the MSW to provide the desired particulate slag suitable for use to replace sand or fine aggregates in a concrete. For example, the wastewater sludge, the freshwater sludge and the sludge incineration ash may be selected from one or more of the group consisting of a dewatered alum sludge, a dried sludge from a wastewater treatment facility, bottom ash particles formed from incineration of a sludge, and sludge incineration fine ash particles.

Dewatered alum sludge may be generated from a waterworks plant apply flocculation and coagulation for freshwater treatment.

Dewatered sludge may be generated from a water reclamation plant.

Dried sludge was generated from a municipal wastewater treatment facility (water reclamation plant) after anaerobic digestion, dewatering and drying processes.

Bottom ash was generated from a commercial sludge incineration facility where the inorganic residues sintered to form granular ash particles.

Sludge incineration fine ash may be generated from a commercial sludge incineration facility that generate ash residues in fine particles.

As will be appreciated, the method disclosed herein may be suitable for use on a commercial/industrial scale and so the gasifier, or the apparatus to which the gasifier is attached, may be one that can produce significant quantities of the desired particulate slag.

As such, any suitable loading rate may be used herein. For example, the loading rate for the municipal solid waste may be from 200 to 500±110 kg/h, such as from 222 to 428±108 kg/h

and the loading rate of the one or more of the wastewater sludge, freshwater sludge and the sludge incineration ash is commensurate with the weight:weight ratios described hereinbefore.

In certain embodiments that may be mentioned herein, the total loading rate for one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash may be from 40 to 250±60 kg/h, such as from 42 to 217±60 kg/h and the loading rate of the municipal solid waste is commensurate with the weight:weight ratios described hereinbefore.

As will be appreciated, the loading ratios provided above are based on the use of a Waste-to-Energy Research Facility (WTERF) with a designed capacity of treating 11.5 t/day for MSW. As such, the loading rates and ratios may be scaled up accordingly based on the use of a commercial/industrial gasification system or apparatus, provided that the ratios between the components are maintained accordingly.

As noted hereinbefore, the particulate slag produced by this co-gasification has particularly good properties that make it suitable to replace sand or fine aggregates in a concrete (or a mortar), amongst other things. Thus, in a second aspect of the invention, there is provided a particulate slag suitable for use to replace sand or fine aggregates in a concrete, the slag's elemental composition comprising each of Ca, Si, Al, Na, Fe, Mg, P, K, Ti, and Mn in an amount greater than 1g/kg. The elemental composition may be determined in the manner discussed in the examples section below.

The particulate slag disclosed herein may have any of the following features:

- (i) a mean particle size diameter that may be less than 40 mm, optionally wherein the mean particle size diameter is from 1 to 5 mm, such as from 2.0 to 3.1 mm;
- (ii) the water absorption of the slag may be from 0.5 to 0.7%, such as about 0.64%;
- (iii) the specific gravity of the slag may be from 2.6 to 2.9, such as from 2.72 to 2.8;
- (iv) the bulk density of the slag may be from 1.2 to 1.6 g/cm³, such as from 1.31 to 1.51 g/cm³;
- (v) the particle density of the slag on an oven-dried basis may be from 2.5 to 3.0 g/cm³, such as from 2.74 to 2.80 g/cm³.

As will be appreciated, the particulate slag may have two or more, such as three or more, such as four or more of the properties listed in (i) to (v) above. In particular embodiments of the invention that may be mentioned herein, the particulate slag may have all of the properties listed in (i) to (v) above.

The particulate slag disclosed herein may have angular to sub-angular morphology. This morphology may be advantageous because the higher friction between the angular morphology of the aggregates could lead to interlocking behaviour that can contribute to increased construction material strength (e.g. or a mortar or a concrete).

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The particulate slag may be provided in a crystalline solid form or in an amorphous solid form. In particular embodiments of the invention the particulate slag may be in an amorphous solid form. The form of the particulate slag may be determined through the use of any suitable X-ray diffraction method, such as powder diffraction.

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As noted hereinbefore, the particulate slag suitable for use to replace sand or fine aggregates in a concrete may be used to form a mortar. As such, in a further aspect of the invention, there is provided a mortar comprising:

- 15 a particulate slag as described herein, or a particulate slag obtainable from a method according as described herein; and
- a cement.

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In the current invention, the various types of sludge-derived slag generated from the different co-gasification conditions may be mixed with cement at a weight ratio of 1:1 to form a slag mortar.

As will be further appreciated, the particulate slag suitable for use to replace sand or fine aggregates in a concrete may also be used to form a concrete. As such, in a further aspect of the invention, there is provided a concrete comprising:

- 25 a particulate slag as described herein, or a particulate slag obtainable from a method as described herein;
- a cement;
- an admixture; and
- coarse aggregates.

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The concrete may have one or more of the following properties:

- (ia) a water absorption of from 1.85 to 2.00%;
 - (ib) a resistance to chloride ingress, once cured, of from 1379 to 1877 coulombs; and
 - (ic) a compressive strength comparable to a concrete made using sand instead of the
- 35 particulate slag.

The slag concrete may be made from the sludge-derived slag with cement and aggregates (cement : slag : aggregates = 1 : 2 : 3).

As will be appreciated, the concrete may have one, two or all three of the properties mentioned above.

As noted herein, there is provided a set of well-engineered and predictable concrete products that can be produced using a particulate slag that can be derived from the co-gasification of a municipal solid waste and one or more of a wastewater sludge, a freshwater sludge and a sludge incineration ash. This particulate slag may have one or more of the following properties.

- a. Low environmental impact green concrete due to the elimination of the need for excavation of natural sand.
- b. Low water absorption (1.85 to 2.00%).
- c. High resistance to chloride ingress (1379 to 1877 coulombs with grading identified as low) and good durability.
- d. Comparable compressive strength to typical sand concrete and potentially applicable for both non-structural and structural applications.

Further advantages associated with the current invention include the following.

- The particulate slag produced herein is derived from a renewable and environmentally friendly co-gasification method that reduces landfill.
- The particulate slag can be used in the formation of construction materials to conserve conventional natural sand resources.
- The particulate slag may be generated using locally-generated sludge and wastes using a high temperature slagging gasification process. This method may nevertheless reduce the carbon footprint, as there is no need to transport the particulate slag over a long distance, as may be the case with sand.
- Better predictability of the workability, slump loss and optimum water usage of different design mixes of different co-gasification sludge-derived slag.
- Reduce the utilization of natural resources by replacing conventional natural sand with cogasification sludge-derived slag.
- Provide substantial cost savings for end-users as compared to imported sand required the additional costs for transportation and import tariffs.
- Reduce the amount of final residual wastes to landfill. This may also contribute to close the waste loop by achieving zero waste.

The current invention can be applied to produce construction materials derived from a co-gasification sludge-derived slag. The possible applications include:

1. as a green and sustainable construction material since the sludge-derived slag is a waste-derived material. This can provide benefits in terms of resource efficiency, energy conservation and space conservancy;
2. as a supplementary material to the conventional concrete products with fully replacement of sand with sludge-derived slag to conserve the natural resources; and
3. as a low permeability concrete that can be suitable for the use in relatively more aggressive environment with exposure to chlorides and sulphate (such as coastal protection).

Further aspects and embodiments of the invention may be described by reference to the following clauses.

1. Use of co-gasification sludge-derived slag in concrete production to replace sand fully, with high workability and strength.

2. A set of design recipes for the use of co-gasification sludge-derived slag in concrete production with the properties of:

- a. low water absorption for better control of workability; and/or
- b. angular particle morphology can promote bonding between the cement paste and the aggregates; and/or
- c. inert material with no detrimental reactivity towards concrete production and subsequent applications; and/or
- d. low metal, heavy metal, chloride, and sulphates leaching potential and safe for reutilization as a waste-derived product.

3. A set of well-engineered and predictable concrete products produced of co-gasification sludge-derived slag with the properties of:

- a. low environmental impact green concrete (eliminates the need for excavation of natural sand); and/or
- b. low water absorption and water permeability; and/or
- c. high resistance to chloride ingress and good durability; and/or
- d. comparable compressive strength to typical sand concrete and potentially applicable for both non-structural and structural applications.

Further aspects and embodiments of the invention will now be described by reference to the following non-limiting examples.

Examples

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Materials

Municipal solid waste (MSW) was collected from Nanyang Technological University main campus (50 Nanyang Avenue, Singapore 639798). Dewatered municipal sewage sludge (M-DWS) was collected from a municipal wastewater treatment plant (or named as Water Reclamation Plant in Singapore, WRP 1). Dewatered alum waterworks sludge (Al-WWS) was collected from a freshwater treatment plant (or named as Waterworks). Dried municipal sewage sludge (DS) was collected from a different municipal wastewater treatment plant (WRP 2). Sludge incineration bottom ash (BA) was collected from a commercial sludge incineration facility (SIF 1) employing a vortex incinerator. Sludge incineration mixed ash (IMA) was collected from a commercial sludge incineration facility (SIF 2) employing a fluidized bed incinerator. Dewatered industrial sewage sludge (I-DWS) was collected from an industrial wastewater treatment plant (WRP 3). All the WRPs and SIFs are located in Singapore. Dewatered alum waterworks sludges derived slag (Al-WWS slag), dried municipal sewage sludges derived slag (DS slag), sludge incineration bottom ash derived slag (BA slag), and the mix of sludge incineration fine ashes and dewatered sludge derived slag (MA+M-DWS slag) samples were collected from Waste-to-Energy Research Facility (WTERF) and stored under room temperature in the laboratory prior to be applied as the replacement material for sand for concrete manufacturing.

25 For a representative sampling work, each type of waste material was collected for characterization in three independent batches with a minimum of two weeks' interval between the batches. At least 20 kg of respective sample was collected per batch.

Example 1. Co-gasification and Generation of Slag

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Different types of sludge-derived slag were generated through the co-gasification of MSW with freshwater treatment sludge, sewage sludge and sludge incineration ashes at an 11.5 tonne/day Waste-to-Energy Research Facility (WTERF) in Singapore.

35 As shown in FIG. 1, the WTERF consisted of gasifier/melting furnace, secondary combustion chamber (SCC), boiler, cyclone, gas cooling tower, and bag filter. The feedstock, comprising shredded MSW and secondary waste (sludge and incineration ash), was loaded at the top of

the gasifier, with a weight ratio of sludge and/or ash to MSW ranging from 10-50%, together with biomass charcoal (as auxiliary fuel and melting bed support) and limestone (as an additive to adjust slag viscosity). The bottom of the gasifier was operated at the temperature of 1600 - 2000°C (Heberlein, S. *Journal of Hazardous Materials*, **2022**, 423, 127057). After gasifying, inorganic residues in the gasifier melted to form molten slag and metal (40 - 100 kg/h), and flow down towards the bottom of the melting furnace where the outlet is located. A water quenching system was installed to perform the cooling and granulation for the molten slag outflow from the bottom of the gasifier and subsequently recyclable ferrous metal particles from molten residues during quenching which were separated from the slag through a magnetic separator. Water granulation tank, where the slag quenching is done, has a volume of ~13 m³ and the water is exchanged every week. Quenching water was sampled three times (on day 2, day 4, and day 7 after the water was exchanged, respectively) during normal MSW operation, and measured for trace element concentration for comparison with slag leaching performance. The syngas with particulates (~1200 Nm³/h) went to SCC (900 - 1200 °C) for combustion from the top of the gasifier for complete combustion, where diesel was introduced and applied as auxiliary fuel, whenever applicable. Diesel or water were occasionally used for proper temperature control. The heat of the flue gas was recovered in a boiler (350 - 400 °C) facilitated with a steam turbine for electricity generation. Subsequently, the flue gas and particulates passed through cyclone separator, gas cooling tower (GCT), bag filter in order, and released to the atmosphere after treatment by sorbent. Two types of flue gas treatment sorbents (slaked lime or sodium bicarbonate, respectively, mixed with activated carbon) were applied between GCT and bag filter for emission control. Gasification fly ashes (GFA) from secondary combustion chamber (SCC), boiler, cyclone separator, gas cooling tower (GCT), and bag filter were combined and collected for analysis and disposal. The various collected slag samples are shown in FIG. 2. The details of the co-gasification of wastes and respective feeding rates are listed in Table 1.

To minimise the impacts from composition variation of samples from seasonal changes and sampling location, the demonstration trial was performed within 2 months for all reported testing results where the specific scenario was performed within 4 days, respectively. In addition, the MSW applied was collected from NTU campus while the sludge was sampled from specific water or wastewater treatment plants. The sources of waste applied were fixed during the trial. Furthermore, comprehensive characterization testing of sludge was performed in three individual batches collected over the trial duration which include the actual waste sent to WTERF and the sludge directly sampled from the specific water or wastewater treatment plants.

Table 1. Wastes loading rates for various slag productions.

Slag	Loading rate (kg/h)			Remarks
	MSW	Sludge/Ash	Total	
AI-WWS slag	390±103 (90%)	42±11 (10%)	432±114 (100%)	Dewatered alum sludge was generated from a waterworks plant applying flocculation and coagulation for freshwater treatment.
DS slag	222±67 (50%)	217±60 (50%)	439±127 (100%)	Dried sludge was generated from a municipal wastewater treatment facility (water reclamation plant) after anaerobic digestion, dewatering and drying processes.
BA slag	428±108 (76%)	132±31 (24%)	560±139 (100%)	Bottom ash was generated from a commercial sludge incineration facility where the inorganic residues sintered to form granular ash particles.
MA+M-DWS slag	324±68 (67%)	159±38 (33%)	483±106 (100%)	Sludge incineration fine ash was generated from a commercial sludge incineration facility that generate ash residues in fine particles. Dewatered sludge was generated from a water reclamation plant.

Results and Discussions

It has demonstrated that the co-gasification of sludge/ash with MSW can convert diverse waste streams into high quality and highly stable slag while recover the energy in the wastes, thereby provide an attractive alternative thermal treatment technology for sludge and ash at relatively high loading ratios. Several co-gasification scenarios of MSW with sludge and ash were designed and demonstrated as shown in Table 1.

Dewatered AI-WWS is considered as a non-combustible waste and currently being disposed to landfill. Co-gasification of AI-WWS and MSW (Scenario 1) was to explore the possible

synergistic treatment of combustible and non-combustible wastes. Dried and dewatered sewage sludge are both tested to evaluate the feasibility and performance during co-gasification because of the differences in moisture contents and physical states (granular dried form and sticky dewatered form). However, although the DS (Scenario 2) could be fed directly through the feeder, DWS was found very wet, sticky and clumped easily. Therefore, it is challenging to feed the DWS directly and additionally, the clumped DWS sludge may significantly affect the control of the temperature profiles in the gasifier. Sludge incineration bottom ash (coarse granular particles, BA) and mixed ash (fine powdery particles, MA) were both tested as the BA (Scenario 3) and MA+M-DWS (Scenario 4), as they were having distinctive particle size distribution patterns and are generated from different types of incinerators (vortex incinerator and fluidized bed incinerator, respectively). BA could be fed into the gasifier directly, but MA is of very fine particle size distribution which caused dusting and effective melting issues as the flow of syngas in the gasifier would carry the particles away from the top instead of dropping down to the melting zone. Therefore, MA was mixed with M-DWS at a ratio of 2:5 (Scenario 4). This mixing approach reduced the effective moisture content and stickiness of the M-DWS before entering the gasifier while concurrently resolving the feed issues of MA with very fine particle size. Photos of the mixtures prepared are shown in FIG. 3.

Example 2. Physical and Chemical Properties Characterisation of Various Sludge-Derived Slag

Physical and chemical characterization was carried out on the various sludge-derived slag.

Bulk Density, pH Value and Mass Measurements

Bulk density and pH values were determined as received following ASTM D5057 and US EPA Method 9054D, respectively. Samples were then dried at 105 °C for 24 hours with mass measured before and after drying for moisture content determination.

Particle Size Distribution (PSD)

Particle size distribution of BA and MA were determined following BS EN 933-1-2012 and via a laser diffraction particle size analyser (Mastersizer 2000, Malvern Panalytical, UK).

Water Absorption and Moisture Content Determination

Water absorption and moisture content were tested based on BS EN 1097-6 and BS 1377-2:1990, respectively.

Testing of Slag as Aggregates for Concrete and Geotechnical Properties

A series of physical properties related to the potential of slag being applied as a fine aggregate in concrete production were tested. These include fines content, organic impurities (humus content), water soluble chloride content, acid soluble sulphate content, particle density and water adsorption, bulk density and void density, drying shrinkage, total sulfur content, petrographic examination of aggregates for concrete, potential alkali reactivity, aggregate alkali-silica reactivity (ASR, mortar bar method), fulvo acid, assessment of fines - methylene blue test, total chloride content, and soundness. Tests were conducted according to respective established standards (Table 2).

Table 2. Testing of slag as aggregates for concrete and geotechnical properties.

Method	Description
BS EN 933-1:2012	Determination of particle size distribution - sieving method
BS EN 933-1: 2012	Determination of fine content
BS EN 1097-3:1998	Determination of bulk density and void density
BS EN 1097-6:2013	Determination of relative density and water absorption
BS EN 933-9:2009+A1:2013	Assessment of fines: methylene blue test
BS EN 196-2:2013	Determination of chloride content
ASTM C88:2013	Determination of magnesium sulphate soundness
BS EN 1367-4:2008	Determination of volume stability - drying shrinkage
BS EN 1744-1:2009+A1:2012, 15.1	Determination of potential presence of humus
BS EN 1744-1:2009+A1:2012, 7	Determination of water-soluble chloride salts
BS EN 1744-1:2009+A1:2012, 12	Determination of acid-soluble sulphate
BS EN 1744-1:2009+A1:2012, 11	Determination of total sulphur content
BS EN 1744-1:2009+A1: 2012, 15.2	Determination of fulvo acid content
ASTM C1260	Determination of potential alkali reactivity
BS 1377-2:1990	Determination of moisture content
BS 1377-3:2018	Determination of organic matter content
ASTM C128-15	Determination of specific gravity
ASTM C295/C295M-2019	Petrography test of aggregates

Magnified Images for Morphology Observation

Magnified images for morphology were taken by a stereomicroscope (Olympus, model MVX10).

Results and Discussions

Table 3 shows the moisture content and water absorption of various sludge-derived slag. The various slag has respectively lower moisture content and water absorption of 1-3% and approx. 0.6%, as compared to that of river sand at 11.45% and 2.30% respectively.

Table 3. Moisture content and water absorption of various sludge-derived slag and river sand (BS EN 1097-6)

Characterizations	Al-WWS slag	DS slag	BA slag	MA+M-DWS slag	River sand
Moisture content (%)	1.07	2.18	2.36	2.74	11.45
Water absorption (%)	0.66	0.64	0.60	0.66	2.30

The particle size distributions of the various slag are presented in FIG. 4. Table 4 lists that the particle size distributions (PSD) of various sludge-derived slag were comparable to the river sand and suitable for use as fine aggregates with a grading of G_F85 with accordance to BS EN 933-1. It can be noted that slag sizes are less than 40 mm. The mean diameters of the Al-WWS slag, DS slag, BA slag, and MA+M-DWS slag were around 3.0, 3.1, 2.9, and 2.0 mm, respectively, which were comparable to sand (~ 2.3 mm).

Table 4. Particle size distributions (PSD) of slag and river sand (based on BS EN 933-1: 2012).

Aggregate	Size	Percentage passing by mass			Tolerance in percentage passing by mass				Category G
		2D	1.4D	D	4	1	0.25	0.063	
Fine	D ≤ 4 mm d=0	100	95-100	85-99	(±5)	(±20)	(±20)	(±3)	
Sieve size (mm)		8	6.3	4	4	1	0.25	0.063	G _F 85
Al-WWS slag	0/4	100.0	95.0	85.9	85.9	19.6	2.2	0.0	G _F 85
DS slag	0/4	100.0	98.0	85.0	85.0	15.3	2.0	0.0	G _F 85
BA slag	0/4	100.0	99.0	97.0	97.0	39.4	3.0	1.0	G _F 85
MA+M-DWS slag	0/4	100.0	99.0	98.0	98.0	45.0	5.0	1.0	G _F 85
River sand	0/4	100.0	97.0	90.7	90.7	48.1	16.1	1.83	G _F 85

FIG. 5 shows the pictures and microscopic images of sludge-derived slag, irregular granular with rough surface was observed on the morphology of larger slag while the rodlike structure was presented in smaller slag.

Other physical and chemical properties of sludge-derived slag are listed in Table 5.

Table 5. Properties of various sludge-derived slag.

Test	AI-WWS slag	DS slag	BA slag	MA+M-DWS slag
Fines content, passing 0.063mm sieve by mass (%)	0.3	0.4	0.7	0.9
Bulk density (g/cm ³)	1.51	1.31	1.37	1.38
Particle Density on an oven-dried basis (g/cm ³)	2.78	2.74	2.79	2.79
Particle Density on a saturated and surface-dried basis (g/cm ³)	2.80	2.76	2.80	2.81
Apparent particle density (g/cm ³)	2.83	2.79	2.83	2.85
Total chloride content (% m/m)	<0.01	<0.01	<0.01	<0.01
Organic impurities (-)	Negative test	Negative test	Negative test	Negative test
Potential Alkali Reactivity (-)	Innocuous behaviour	Innocuous behaviour	Innocuous behaviour	Innocuous behaviour
Water absorption (%)	0.66	0.64	0.60	0.66
Specific gravity (-)	2.79	2.78	2.80	2.72
Methylene Blue Value (g/kg)	0.3	0.3	0.3	0.3
Assessment of Fines (g/kg)	0.3	0.3	0.3	0.3
Soundness (% loss)	2	4	2	2
Drying shrinkage (% , shall not exceed 0.075%)	0.035	0.037	0.029	0.035
Potential presence of humus	Negative test (lighter than No.3)	Negative test (lighter than No.3)	Negative test (lighter than No.3)	Negative test (lighter than No.3)
Water soluble chloride content (% m/m dry)	< 0.01	< 0.01	< 0.01	< 0.01
Acid soluble sulphate content (% m/m dry)	0.21	0.55	0.8	0.01
Total sulfur content (% m/m dry)	1	2.01	2.91	1.48
Determination of fulvo acid content (-)	Negative test (lighter than No. 3)	Negative test (lighter than No. 3)	Negative test (lighter than No. 3)	Negative test (lighter than No. 3)
Potential alkali-silica reactivity by mortar-bar (Expansion % after 16 days), very low potential for expansion (below 0.1%)	0.01	0.01	0.01	0.01
Moisture content (%) (BS 1377-2:1990)	1.07	2.18	2.36	2.74
Organic matter content (%)	0.54	0.62	0.62	0.52

Table 5 lists the physical properties of sludge-derived slag. Relatively low amounts of sludge-derived slag ($< 1\%$) were below 0.063 mm passing and achieved the best f_3 grading for the maximum values for fines content (3%, SS EN 12620:2008). Fines higher than 3% can have a detrimental impact on the workability and other properties of concrete. The bulk density of the sludge-derived slag was $1.39 \pm 0.08 \text{ g/cm}^3$, while the particle density was $2.7 \pm 0.02 \text{ g/cm}^3$. The density of the slag was comparable to typical fine aggregates, which typically range between 2.4 and 2.9 g/cm^3 (Kosmatka, S.H. et al., Design and Control of Concrete Mixtures, Portland Cement Association Skokie, IL2002). Total chloride content which could lead to corrosion to the construction material was less than 0.01% m/m. The potential alkali reactivity was tested innocuous behaviour and organic impurities test was negative. The water absorption of various slag was around $0.64 \pm 0.03\%$, while the specific gravity ranged from 2.72 to 2.80. In comparison to conventionally used aggregates (2.64 - 2.75 for specific gravity and 0.6 - 2.3% for water absorption) (Chini, A.R. et al., *Journal of Transportation Engineering*, **2001**, 127, 486; Patil, M., *International Journal of Advances in Mechanical and Civil Engineering*, **2015**, 2; Yacoub, A. et al., *Construction and Building Materials*, **2018**, 158, 464; Quattrone, M. *Construction and Building Materials*, **2016**, 123, 690), the slag demonstrated a comparable specific gravity and absorption rate. The physical properties of sludge-derived slag such as particle density, specific gravity, and water absorption were comparable to common aggregates. This makes it a favourable choice as an aggregate material.

Table 5 also illustrates the chemical properties and stability of sludge-derived slag for use as a fine aggregate by determining the presence of different detrimental/reactive contents in fine aggregates such as sulphate, chlorides, fulvo acid and organic compounds (humus). The possibility of potential alkali-silica reactivity of the sludge-derived slag and the expansion values are all well below the requirement of $< 0.1\%$ suggesting that there is no active content in sludge-derived slag that could lead to detrimental expansion and long-term durability issues.

FIG. 5 presents the petrography analysis and image of sludge-derived slag, visually the sludge-derived slag appeared grey in colour. Sludge-derived slag was angular to sub-angular in morphology with mainly vitreous slag and other opaque contents. Sludge-derived slag consisted of 96.4 - 98.8% of slag and 1.2 - 3.4% of opaque minerals (Table 6). The higher friction between the angular morphology of the aggregates could lead to interlocking behaviour in fresh concrete that can contribute to the construction material strength but possibly decrease the workability (Hu, J. & Wang, K. *Construction and Building Materials*, **2011**, 25, 1196; Li, Z. et al., *Construction and Building Materials*, **2022**, 346, 128417). Additionally, low porosity and water absorption of the sludge-derived slag could compensate for decreased workability.

Table 6. Petrography test of various co-gasification slag (ASTM C295/C295M-2019)

Type	AI-WWS slag	DS slag	BA slag	MA+M-DWS slag
Slag (%)	96.4	96.6	98.8	97.6
Opaque minerals (%)	3.6	3.4	1.2	2.4

Example 3. Chemical Composition of Various Sludge-Derived Slag and Comparison with River Sand

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Determination of Elemental Compositions of Various Materials

Microwave acid digestion (MAD) (USEPA Method 3051A) followed by inductively coupled plasma-optical emission spectrometry (ICP-OES) (Perkin Elmer Optima 8300) was conducted to determine the elemental compositions of various materials.

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X-Ray Diffraction (XRD)

X-Ray Diffraction (XRD) (Bruker, D8 Advance) was used to determine mineralogy.

Results and Discussions

- 15 The chemical composition of the sludge-derived slag and river sand were evaluated by using inductively coupled plasma-optical emission spectrometry (ICP-OES) after microwave digestion as shown in Table 7 and Table 8.

Table 7. Major composition of various sludge-derived slag from ICP-OES (%)

Elements	AI-WWS slag	DS slag	BA slag	MA+M-DWS slag	Sand
Si	8.92	9.07	10.52	12.58	36.58
Ca	15.01	18.75	19.84	23.29	0.54
Al	15.94	8.78	7.83	7.67	6.59
Fe	3.05	2.68	4.66	3.92	0.61
Na	3.08	1.78	1.37	1.95	2.1
Mg	1.04	2.30	1.61	3.14	0.12
Ti	0.39	0.48	0.42	0.45	0.06
K	0.60	0.90	1.81	1.28	3.39
Mn	0.25	0.17	0.17	0.16	0.02

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Table 8. Elemental composition of various sludge-derived slag.

Element	Al-WWS slag (mg/kg)		DS slag (mg/kg)		BA slag (mg/kg)		IMA+DWS slag (mg/kg)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ca	150071	10835	187528	2025	198421	8074	232883	9629
Si	89238	8463	90705	8718	105224	2906	125821	12727
Al	159385	10667	87814	2952	78342	4824	76686	4123
Na	30752	1901	17762	299	13741	167	19493	846
Fe	30475	1739	26821	661	46585	2194	39170	7426
Mg	10370	593	22969	369	16103	537	31433	1950
P	3374	180	41401	535	29681	245	29205	2112
K	5953	323	9009	232	18106	296	12822	477
Ti	3861	209	4812	98	4154	61	4490	155
Mn	2517	156	1708	23	1712	68	1582	73
Ba	1251	74	1318	14	744	21	1100	60
Cr	837	52	435	13	1280	87	474	54
Cu	134.10	12.89	312.19	1.28	482.50	32.16	501.72	174.35
Zn	97.77	15.48	164.28	9.54	251.29	113.63	276.95	9.35
V	26.13	2.05	22.78	0.14	54.39	0.92	27.29	2.13
Sn	8.22	0.61	16.16	0.54	30.69	2.00	41.61	11.22
Ni	2.13	0.39	7.86	1.16	12.01	3.45	19.31	11.19
Hg	4.81	2.13	<1.5	<1.5	2.69	0.36	3.14	0.39
Pb	6.63	0.42	4.57	0.34	13.73	4.85	10.73	0.66
Mo	<1.5	<1.5	2.37	0.26	1.99	0.13	<1.5	<1.5
Sb	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	2.80	0.85
Co	<1.5	<1.5	<1.5	<1.5	4.08	2.68	<1.5	<1.5

In general, the main elements in the sludge-derived slag were Ca, Si, Al, Na, Fe, and Mg. The percentage of Ca, Si and Al are much higher than other components in the sludge-derived slag. Specifically, the total amount of Ca, Si and Al (combined) in Al-WWS slag, DS slag, BA slag, and MA+M-DWS slag were 81.6, 74.3, 74.2, and 75.6%, respectively. Notably, higher Al content was observed in Al-WWS slag (32.6%) as compared to other slag (13 - 18%), which was mainly attributed to the high Al content in the dewatered alum sludge co-gasified. Comparing with river sand, Si in sludge-derived slag is lower while Ca is higher. In addition, high P content (5.1 - 8.4%) was observed in DS slag, BA slag, and MA+M-DWS slag, comparing to Al-WWS slag (0.7%). This could be due to higher P content in sewage sludge and sludge incineration ashes.

FIG. 7 shows the XRD results of the cement and various slag. The sludge-derived slag was composed of a highly amorphous mineral as exhibited by a single broad peak with a 2θ value = 31° representing calcium-alumino-silicates, which agrees well with the chemical composition analysis. The river sand consisted of mainly highly crystalline Quartz and other phyllosilicates such as Muscovite & Chlorite. The mineralogy of cement was mainly consisting of Alite, belite, Gypsum, Tricalcium aluminate & Calcium aluminoferrite.

Example 4. Leaching Performance of Various Sludge-Derived Slag

To evaluate the environmental impacts of sludge-derived slag, TCLP, batch leaching, and column leaching were conducted.

Leaching Behaviour Assessment

To assess the leaching behaviour of heavy metals, the Toxicity Characteristic Leaching Procedure (TCLP), batch leaching, and column leaching tests were conducted following the guidelines of USA EPA Method 1311, NS EN12457-1 and 2:2002, and DD CEN/TS 14405:2004, respectively. The leachate was subjected to analysis using various techniques, including ICP-OES, inductively coupled plasma-mass spectrometry (ICP-MS) (ThermoScientific iCAP Q) and ion chromatograph (IC, Dionex, ICS-1100). These analytical methods were employed to determine and quantify the presence of specific elements and ions in the leachate. The obtained leaching results from the leachate analysis were subsequently compared to TCLP regulatory levels (RLs), EU waste acceptance criteria for inert waste landfill (2003/33/EC: Council Decision by European Union), and the draft Reference Values (RVs) from National Environment Agency (NEA), Singapore, for re-utilization of waste-derived materials, based on the batch leaching test (EN 12457-1:2002). Triplicates were performed for each sludge-derived slag sample.

Results and Discussions

The leaching results for sludge-derived slag are present in Tables 9-12 and compared against TCLP regulatory levels (RLs), EU waste acceptance criteria for inert waste landfill (2003/33/EC: Council Decision by European Union), and the draft Reference Values (RVs) from National Environment Agency (NEA), Singapore, for re-utilization of waste-derived materials, based on the batch leaching test (EN 12457-1:2002).

Table 9. TCLP of various sludge-derived slag.

	RL*	Leachate concentration (mg/L)							
		Al-WWS slag		DS slag		BA slag		IMA+DWS slag	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
As	5	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Ba	100	0.802	0.020	0.176	0.004	0.109	0.037	0.192	0.031
Cd	1	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Cr	5	0.218	0.002	0.027	0.003	0.027	0.009	0.025	0.003
Cu	100	0.050	0.013	0.322	0.021	0.218	0.015	0.186	0.048
Fe	100	12.48	1.219	10.30	2.661	7.833	6.315	19.96	2.050
Pb	5	0.046	0.043	<0.02	-	<0.02	-	<0.02	-
Mg	50	3.867	0.382	6.960	0.401	3.673	0.114	18.99	1.480
Hg	0.2	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Ni	5	0.067	0.000	0.047	0.003	0.128	0.017	0.119	0.003
Se	1	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Ag	5	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Zn	100	1.283	1.036	0.605	0.118	0.449	0.194	0.258	0.045

*RL: TCLP regulatory levels.

Table 10. Batch leaching L/S 2 of various sludge-derived slag.

	EU Inert Criteria	Leachate concentration (mg/kg)							
		Al-WWS slag		DS slag		BA slag		MA+M-DWS slag	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
As	0.1	0.0013	0.0009	0.0009	0.0001	0.0009	0.0003	<0.0005	-
Ba	7	0.0049	0.0012	0.0332	0.0016	0.0142	0.0034	0.172	0.0092
Cd	0.03	<0.0005	-	<0.0005	-	<0.0005		<0.0005	-
Cr	0.2	0.0064	0.0006	0.0054	0.0001	0.0073	0.0007	0.0046	0.0005
Cu	0.9	0.0129	0.0057	0.0096	0.0008	0.0091	0.0004	0.0077	0.0023
Hg	0.003	<0.0005	-	0.0024	0.0001	0.0011	0.0001	<0.0005	-
Mo	0.3	0.0091	0.0011	0.027	0.0006	0.0104	0.0003	0.0095	0.0015
Ni	0.2	0.0009	0.0005	<0.0005	-	<0.0005	-	<0.0005	-
Pb	0.2	<0.0005	-	<0.0005	-	<0.0005		0.0016	0.0005
Sb	0.02	0.0101	0.0017	0.0086	0.0002	0.0098	0.0011	0.0054	0.0004
Se	0.06	0.0011	0.0003	0.0022	0.0001	<0.0005		0.0007	0.0001
Zn	2	0.0092	0.0065	<0.0005	-	0.0022	0.002	<0.0005	-
Chloride	550	6.3683	1.5887	4.3048	0.2292	3.3952	0.3364	6.312	1.2524
Fluoride	4	0.2866	0.0467	1.1763	0.0223	0.6795	0.0488	0.5872	0.0713
Sulphate	560	9.9755	2.0981	17.2803	0.2145	4.9628	0.3765	8.2204	1.6125
TOC	30,000	5.1127	0.5289	4.2040	0.8596	2.7447	0.2654	3.0380	0.8823

Table 11. Column leaching of various sludge-derived slag.

	EU Inert Criteria	Leachate concentration (mg/kg)							
		Al-WWS slag		DS slag		BA slag		MA+M-DWS slag	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
As	0.006	0.00007	0.00001	<0.00001	-	0.00012	0.00003	<0.00001	-
Ba	0.4	0.00049	0.00009	0.00067	0.00002	0.00028	0.00015	0.02058	0.00244
Cd	0.002	<0.00001	-	<0.00001	-	<0.00001	-	<0.00001	-
Cr	0.01	0.00011	0.00000	0.00074	0.00035	0.00048	0.00034	<0.00001	-
Cu	0.06	0.00078	0.00064	0.00036	0.00002	0.00111	0.00028	0.00309	0.00114
Hg	0.0002	<0.00001	-	0.00018	0.00005	<0.00001	-	<0.00001	-
Mo	0.02	0.00058	0.00002	0.00461	0.00235	0.00189	0.00071	0.00163	0.00032
Ni	0.012	0.00008	0.00002	<0.00001	-	0.00148	0.00195	<0.00001	-
Pb	0.015	0.00005	0.00000	<0.00001	-	<0.00001	-	0.00088	0.00027
Sb	0.01	0.00842	0.00235	0.00114	0.00078	0.00144	0.00098	0.00908	0.00856
Se	0.004	<0.00001	-	0.00026	0.00023	<0.00001	-	0.00037	0.00016
Zn	0.12	0.00086	0.00053	0.00076	0.00093	0.00051	0.00058	0.00689	0.00114
Chloride	46	2.43799	0.39203	2.98361	1.92905	3.71512	1.59618	3.19926	0.22180
Fluoride	0.25	0.03188	0.00448	0.05653	0.00441	0.07974	0.01787	0.15634	0.03521
Sulphate	150	1.68820	0.00139	5.29097	0.00859	2.93258	0.00687	1.10400	0.00069

All leaching elements from the sludge-derived slag were below TCLP regulatory levels and classified as “non-hazardous”. The elements Mg and Fe reached 7.35 - 37.98% of the limit and 7.83 - 19.96% of the limit, respectively. Others were below 5% of the regulatory levels. Meanwhile, the low leachate concentrations of sludge-derived slag demonstrated the batch leaching were “inert” under EU waste acceptance criteria for landfill, which were comparable to the slag from the gasification of MSW reported previously (Heberlein, S. et al., *Journal of Hazardous Materials*, **2022**, 423, 127057). For the batch leaching, the element close to the leaching limit was Hg which was 36.67 - 80.00% of the EU Inert Criteria. For Sb and fluoride, the measured values were respectively 27.00 - 50.50% and 7.17 - 29.41% of the criteria. Other elements remained below 5% of the criteria. The other elements in column leaching were “inert” under EU waste acceptance criteria. The leaching of heavy metals from various slag shown in Table 12 basically meets the draft Reference Values (RVs) from National Environment Agency (NEA), Singapore, for re-utilization of waste-derived materials and EU leaching criteria for inert waste landfill (2003/33/EC: Council Decision by European Union), based on the batch leaching test (EN 12457-1:2002). It can be concluded that the sludge-derived slag would not pose a severe environmental impact.

Table 12. Leaching performance of various sludge-derived slag using EN 12457-1:2002 and compared to the NEA's reference values (RVs) for reutilization of waste-derived materials in Singapore and the waste acceptance criteria based on 2003/33/EC: Council Decision by European Union.

Elements	Al-WWS slag	DS slag	BA slag	MA+M-DWS slag	RVs	Waste acceptance criteria		
						Inert	Non-hazardous	Hazardous
As	<0.01	<0.01	<0.01	<0.01	0.01	0.1	0.4	6
Sb	0.015	<0.01	<0.01	<0.01	0.04	0.02	0.2	2
Ba	<0.1	<0.1	<0.1	<0.1	2	7	30	100
Cd	<0.001	<0.001	<0.001	<0.001	0.004	0.03	0.6	3
Cr*	<0.01	<0.01	<0.01	0.012	0.02	0.2	4	25
Cr(VI)	<0.01	<0.01	<0.01	<0.01	0.01			
Co	<0.01	<0.01	<0.01	<0.01	0.01			
Cu	0.015	<0.01	<0.01	<0.01	0.09	0.9	25	50
Mn	<0.1	<0.1	<0.1	<0.1	0.3			
Hg	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	0.0003	0.05	0.5
Mo	<0.1	<0.1	<0.1	<0.1	0.2	0.3	5	20
Ni	<0.01	<0.01	<0.01	<0.01	0.02	0.2	5	20
Pb	<0.01	<0.01	<0.01	<0.01	0.02	0.2	5	25
Na	<0.01	<0.01	<0.01	<0.01	400			
Ag	<100	<100	<100	<100	0.01			
Se	0.017	<0.01	<0.01	<0.01	0.02	0.06	0.3	4
Sn	<0.01	<0.01	<0.01	<0.01	0.1			
V	<0.1	<0.1	<0.1	<0.1	0.01			
Zn	<0.1	<0.1	<0.1	<0.1	0.2	2	25	90
Br ⁻	<0.01	<0.01	<0.01	<0.01	0.5			
Cl ⁻	<10	<10	<10	<10	300	550	10000	17000
F ⁻	<1	<1	<1	<1	3	4	60	200
P	<0.1	0.1	<0.1	<0.1	0.5			
SO ₄ ²⁻	<0.01	<0.01	<0.01	<0.01	500	560	10000	25000
TOC	4.56	5.58	5.71	3.57	50	240	380	480

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Example 5. Sludge-derived Slag Mortar Specimens and Concrete Specimens Preparation Procedure

The performance of slag mortar could potentially be further improved with the optimization of the concrete production recipe for slag through the adjustment of water-to-cement ratio (W/C) and the use of superplasticizer (SP).

Sludge-derived Slag Mortar Specimen Preparation

For the preparation of mortar specimen, 300 g cement (EnGro Portland Cement from Buildmate (S) Pte Ltd), 300 g slag or sand (river sand from Buildmate (S) Pte Ltd), and 90 g deionized water (DI water) were added into a mixer with a low mixing speed of 150 rpm. The

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mixer was continuing mixing for 3 minutes at low speed of 150 rpm, followed by 2 minutes at medium speed of 280 rpm. Then the mixture was transferred to silica molds with dimensions of 5 × 5 × 5 cm and demolded after curing for 24 hours at room temperature. The mortar samples were cured, which durations were set at 3, 7, 28, 90, and 180 days before crushing through the compressive strength test in Example 7.

Sludge-derived Slag Concrete Specimen Preparation

Similar to the preparation of mortar specimen, the concrete specimen was mixed with 100 g cement, 200 g slag, 300 g aggregate, 0.5 g admixture, and 40 g water. The samples were gone through the casting, curing, and crushing after certain days of curing durations for further testing.

Mix Design for Various Slag with Cement

For various slag, same ratio of water : cement : slag = 35 : 100 : 100 was applied for mortar specimen and water : cement : slag : aggregates : admixture = 40 : 100 : 200 : 300 : 0.5 for concrete specimen as shown in Table 13. A preliminary assessment has been performed based on the properties of the slag and mortar preparation trial to determine the selected water-to-cement ratio. Aggregates were 20 mm stones and superplasticizer (Sika, Viscocrete 3100) was used for admixture.

Table 13. Mix design for various slag with cement.

S/N	Water (mL)	Cement (g)	Slag (g)	Aggregates (g)	Admixture (g)	Remarks
1	350	1000	1000	NA	NA	AI-WWS slag mortar
2	350	1000	1000	NA	NA	DS slag mortar
3	350	1000	1000	NA	NA	BA slag mortar
4	350	1000	1000	NA	NA	MA+M-DWS slag mortar
5	400	1000	2000	3000	5	AI-WWS slag concrete
6	400	1000	2000	3000	5	DS slag concrete
7	400	1000	2000	3000	5	BA slag concrete
8	400	1000	2000	3000	5	MA+M-DWS slag concrete

Example 6. Leaching Performance of Various Sludge-Derived Slag Mortar

To further evaluate the potential of sludge-derived slag as the construction material, the TCLP and batch leaching were performed on the sludge-derived slag mortar. Different sludge-

derived slag mortar specimens were prepared by following the protocol disclosed in Example 5. The leaching results of the mortar specimens were obtained by following the protocol disclosed in Example 4.

5 Results and Discussions

The leaching results of the mortar from different sludge-derived slag are present in Table 14 and Table 15.

For TCLP tests, all leaching elements from the sludge-derived slag mortar were lower than 10% of TCLP regulatory levels and classified as “non-hazardous”. Nonetheless, for batch leaching, Ba (7.29 mg/kg in DS slag mortar and 7.32 mg/kg in BA slag mortar) was slightly above the limit values for waste acceptable at landfills for inert waste (7 mg/kg), which was comparable to the leaching performance of mortar by incineration fly ash or gasification fly ash (~10 mg/kg) (Viet, D.B. et al., *Journal of Hazardous Materials*, **2020**, 398, 122906). The leachate concentrations of Ba were still below limit values for non-hazardous waste (30 mg/kg for Ba). The other elements were classified as “inert” under EU waste acceptance criteria.

Table 14. TCLP of various sludge-derived slag mortars.

	RL*	Leachate concentration (mg/kg)							
		Al-WWS slag		DS slag		BA slag		MA+M-DWS slag	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
As	5	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Ba	100	3.215	0.931	4.955	2.821	6.671	1.068	3.448	0.710
Cd	1	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Cr	5	0.036	0.012	0.093	0.037	0.140	0.013	0.078	0.016
Cu	100	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Fe	100	0.064	0.025	0.040	0.024	0.135	0.063	0.074	0.017
Pb	5	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Mg	50	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Hg	0.2	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Ni	5	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Se	1	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Ag	5	<0.02	-	<0.02	-	<0.02	-	<0.02	-
Zn	100	<0.02	-	<0.02	-	<0.02	-	<0.02	-

*RL: TCLP regulatory levels.

Table 15. Batch leaching L/S 2 of various sludge-derived slag mortars.

	EU Inert Criteria	Leachate concentration (mg/kg)							
		Al-WWS slag mortar		DS slag mortar		BA slag mortar		MA+M-DWS slag mortar	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
As	0.1	<0.001	-	<0.001	-	<0.001	-	<0.001	-
Ba	7	4.5186	0.9352	7.2919	1.0981	7.3209	0.4554	4.0300	0.1147
Cd	0.03	<0.001	-	<0.001	-	<0.001	-	<0.001	-
Cr	0.2	0.0546	0.0111	0.1540	0.0034	0.1587	0.0057	0.0940	0.0018
Cu	0.9	0.0097	0.0025	0.0043	0.0005	0.0029	0.0002	0.0128	0.0012
Hg	0.003	<0.001	-	<0.001	-	<0.001	-	<0.001	-
Mo	0.3	0.0631	0.0174	0.1226	0.0023	0.1109	0.0022	0.0947	0.0053
Ni	0.2	<0.001	-	<0.001	-	<0.001	-	<0.001	-
Pb	0.2	0.0107	0.0021	0.0087	0.0002	0.0120	0.0003	0.0105	0.0002
Sb	0.02	<0.001	-	<0.001	-	<0.001	-	<0.001	-
Se	0.06	0.0012	0.0003	0.0013	0.0001	0.0013	0.0001	0.0012	0.0001
Zn	2	0.0041	0.0028	<0.001	-	<0.001	-	0.0076	0.0005
Chloride	550	13.7195	5.1063	21.2241	0.8191	21.4905	0.3858	21.5961	0.3885
Fluoride	4	1.5616	0.0116	1.7121	0.0231	1.6527	0.0218	1.6008	0.0135
Sulphate	560	6.7390	0.5813	13.0116	2.7404	20.7479	1.8891	8.6000	0.5583
TOC	3,000	20.8400	0.3930	28.0800	1.0220	25.8330	0.8300	22.3130	2.0910

Example 7. Compressive Strength Test of Sludge-derived Slag Mortar and Cement Specimens

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The mortar specimens were prepared as described in the protocol disclosed in Example 5.

Preparation of Sand Mortars

10 The sand mortars were prepared to compare with the performance of slag mortars. Similar to the preparation of sludge-derived slag concrete specimen, 300 g cement (EnGro Portland Cement from Buildmate (S) Pte Ltd), 300 g sand (river sand from Buildmate (S) Pte Ltd), and 90 g deionized water (DI water) were added into a mixer with a low mixing speed of 150 rpm. The mixer was continuing mixing for 3 minutes at low speed of 150 rpm, followed by 2 minutes at medium speed of 280 rpm. Then the mixture was transferred to silica molds with dimensions
15 of 5 × 5 × 5 cm and demolded after curing for 24 hours at room temperature.

Compressive Strength Test

Compressive strength was tested in accordance with BS EN 12390-3: 2019.

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Results and Discussions

Compressive strength tests were conducted on the sludge-derived slag mortar and sand mortar (as a control for comparison). FIG. 8 displays the compressive strength of the slag mortars and sand mortar for up to 180 days. After curing for 3 days, all slag mortars showed the compressive strength of around 30.0 ± 1.1 MPa, except for MA+M-DWS slag mortar was 47.6 MPa, which was higher than the sand mortar (44 MPa). A similar result was found at 7 days of age, other than MA+M-DWS slag mortar of 53.2 MPa, the compressive strengths of other slag mortars ranged 39.3 - 42.6 MPa. AI-WWS and MA+M-DWS slag mortars achieved compressive strength results of above 50 MPa at 28 days, while the other two sludge-derived slag mortars had compressive strength below 50 MPa. All mortars achieved compressive strength results of above 50 MPa at 90 days with BA slag mortar showing a lower compressive strength at 51.2 ± 4.7 MPa. Generally, the compressive strength increased from curing for 3 to 90 days. For long-term testing of 180 days, the compressive strengths had no significant difference from those of 90 days. It indicates the high level of hydration of cement is successfully achieved and the deterioration of sludge-derived slag mortar over a longer duration is not significant. It is important to note that, AI-WWS slag mortar and MA+M-DWS slag mortar exhibit better performance in compressive strength of above 60 MPa at 180 days. Although the composition content and water absorption of sludge-derived slag are different from the river sand, the sludge-derived slag mortars show excellent performance as river sand in compressive strength and present the possibility to replace it.

The compressive strength of sludge-derived slag concretes at 3, 7 and 28 days respectively are shown in Table 16. All sludge-derived slag concretes demonstrate higher 28 days compressive strength of above 60 MPa.

Table 16. Compressive strength of sludge-derived slag concretes (BS EN 12390-3: 2019).

Compressive (MPa)	AI-WWS slag concrete	DS slag concrete	BA slag concrete	MA+DWS slag concrete
3 days	50.9	52.2	52.1	46.5
7 days	52.3	54.7	57.1	49.8
28 days	64.9	67	63.1	60.8

Example 8. Physical and Chemical Properties Characterisation of Sludge-derived Slag Concrete Specimens

The characterisations were carried out by following the protocols described in Example 2, Example 3, and the current Example.

Length Change and After Exposure to Sulphate Solution

Length change of hydraulic cement mortar and after exposure to sulphate solution were based on ASTM C157/C157M-17 and ASTM C1012/C1012M-18b, respectively.

Coefficient of Water Permeability Test - HDB Test Method

A cylindrical specimen of known dimensions is used, and a constant pressure head of water is applied to the specimen to allow the water to pass through it in a given period of time. The coefficient of permeability is then calculated based on the results.

Accredited Testing for Concrete

The other properties of sludge-derived slag derived concrete prepared based on the design mix developed were tested and shown in Table 17.

Table 17. Accredited testing for concrete.

Method	Description
ASTM C1012/C1012M -18b	Length change after exposure to sulfate solution
ASTM C157/C157M-17	Length change of hydraulic cement mortar
ASTM C1202:2019	Rapid chloride permeability test
BS 1881-121:1983	Static modulus of elasticity
BS EN 12350-2:2019	Slump test
BS EN 12350-7:2009	Air content
BS EN 480-4:2005	Bleeding
ASTM C403/C403M-16	Concrete setting time
BS EN 12390-3:2019	Compressive strength
BS 1881: Pt122:2011+A1:2020	Water absorption
BS EN 12390-8:2019	Water penetration depth

Results and Discussions

FIG. 9 shows the XRD diffractogram of various sludge-derived slag mortars at 28 days. A broaden peak of amorphous calcium silicate hydrate was detected at $2\theta = 30$ to 35° due to

the scattering. Ettringite and portlandite respectively can be observed at $2\theta = 16^\circ$ and 18° as reacted products. The peaks of alite and belite can also be observed illustrating that the hydration was not complete within 28 days. Other peaks observed in the control are due to the different minerals found in the construction sand, indicating the sludge-derived slag is inert in nature.

Shrinkage is unavoidable during the concrete dries because of moisture loss. It is detrimental as it introduces internal tensile stress on restrained concrete resulting in cracking in early age within days or weeks. The typical allowable shrinkage should be lower than 0.05% (water curing) or 0.04% (no curing) according to ASTM C157/C157M-17. The autogenous shrinkage due to the loss of water related to the hydration of cement without external loss through evaporation is accounted for the first 28 days. The next 28 days of dry conditioning is applied to investigate the drying shrinkage due to loss of moisture from the fine pores or carbonation shrinkage. In Table 18, all the sludge-derived slag concretes meet the requirement for both conditions. In accordance with ASTM C1012/C1012M-18b, a maximum of 0.1% expansion for moderate sulfate resistance and 0.05% expansion for severe sulfate resistance are allowed typically. In Table 19, all sludge-derived slag concretes are suitable even for use in severe sulfate environment.

Table 18. Length change of hydraulic cement mortar (ASTM C157/C157M-17).

Day (After cast)	Linear length change %			
	AI-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
1	0	0	0	0
28	0.0051	0.0057	0.0055	0.0055
32	-0.0116	-0.0108	-0.0094	-0.0114
35	-0.0164	-0.0147	-0.0131	-0.0153
42	-0.0191	-0.0186	-0.0173	-0.0207
59	-0.0263	-0.0259	-0.0239	-0.0246

Table 19. Length change after exposure to sulfate solution (ASTM C1012/C1012M-18b).

Week (After cast)	Linear length change %			
	AI-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
1	0.0105	0.0100	0.0092	0.0087
2	0.0137	-0.0458	0.0137	-0.0587
3	0.0170	0.0173	0.0167	0.0182
4	0.0212	0.0185	0.0198	0.0123
8	0.0295	0.0258	0.0238	0.0185
13	0.0342	0.0285	0.0272	0.0222
15	0.0343	0.0288	0.0277	0.0257

The permeability of concrete is significant to the structures that are frequently in contact with water, which is related to the durability of the concrete against long-term deterioration under exposure to the weather. Typically, the average coefficient of permeability to water of conventional concrete ranges from 10^{-12} to 10^{-10} m/s. The coefficients of permeability to water of all sludge-derived slag concretes are lower than 10^{-12} m/s in Table 20.

Table 20. Coefficient of water permeability test - HDB test method.

Test	Al-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
Average coefficient of permeability (m/s)	5.351×10^{-13}	5.272×10^{-13}	5.318×10^{-13}	5.624×10^{-13}

Penetrating chloride is also expected to affect the solubility of major and trace elements in the pore solution (Müllauer, W. et al., *Cement and Concrete Composites*, **2012**, 34, 618). The rapid chloride permeability test (RCPT) is a common method to rapidly access the durability of the concrete, specifically the resistance against chloride ion penetrability based on the amount of charge passed. In Table 21, all sludge-derived slag concretes have low chloride ion permeability in the range from 1379 to 1877 coulombs.

Table 21. Chloride permeability test (ASTM C1202:2019).

Test	Al-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
Charge passed (coulombs)	1664	1843	1526	1379
Grading	Low	Low	Low	Low

The modulus of elasticity of the concrete which is an indicator of strength measures the stiffness of the concrete. Concrete with higher modulus of elasticity can withstand higher stress but also becomes more brittle. Table 22 shows the modulus of elasticity of the designed slag concrete ranges from 34 to 37 GPa which is well within the typical range of 30 to 50 GPa for concrete and suitable for use for non-structural and structural applications.

Table 22. Static modulus of elasticity (BS 1881-121:1983).

Test	Al-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
Modulus of Elasticity (GPa)	35.5	36.5	34.5	36.5

Table 23 shows the slump loss (mm), air content and bleeding for all the sludge-derived slag concretes. The slump loss of all the designs is from 15 mm to 30 mm. The typical range of air content in concrete is around or less than 6% and the air contents of all sludge-derived slag concretes are lower than 6%, illustrating relatively higher density and likely lesser entrapped air which could compromise strength and durability. The bleedings of all sludge-derived slag concretes are 0, indicating the water is not in excess and there is no segregation between the solid and liquid within the concrete mixture. This indicates the coherence of slag with the conventional concrete making materials, which are the cement and stone.

Table 23. Slump test (BS EN 12350-2:2019), Air content (BS EN 12350-7: 2009), and Bleeding (BS EN 480-4:2005).

Test	AI-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
Slump (mm)	20	20	20	25
Air content (%)	2.3	2.1	2.7	1.3
Bleeding (%)	0	0	0	0

For the concrete setting time, the initial refers to the time the cement paste starts hardening (start losing plasticity) and final setting time is the time taken for cement paste to harden enough to resist the penetration of a 5mm needle. Typically, the initial setting time should be above 1 hour to ensure it is not too rigid and give sufficient time to transport and place the concrete while the final setting time should not be longer than 10 hours to ensure adequate gain of strength to achieve structural integrity at the initial hydration. In Table 24, the initial setting time of all sludge-derived slag concretes gives sufficient time to place the concrete before hardening and final setting time is not exceeding the 10 hours requirement. Concrete setting time provides important indication for the actual concrete batching process at the batching plant and the construction site.

Table 24. Concrete setting time (ASTM C403/C403M-16).

Parameter	AI-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
Average Initial Setting time (h)	3.00	3.58	3.33	3.58
Average Final Setting time (h)	4.00	4.83	4.75	5.58

Table 25 shows the water absorption and water penetration of the various sludge-derived slag concretes. The water absorption and penetration test are both popular methods of determining

the water-tightness of the concrete which are related to the durability. The water absorption of all sludge-derived slag concretes are lower than the 3% requirement in BS6349 (British Standard, B., 6349-1: 2000 “*Maritime Structures*”. Part 1: Code of Practice). For the water penetration test, it measures the penetration depth of the water under hydrostatic pressure to determine the permeability of the concrete, lesser penetration indicates better durability. The slag concrete design demonstrated a penetration depth of 11-17mm.

Table 25. Water absorption (BS 1881: Pt122: 2011+A1: 2020) and penetration depth of water under pressure (BS EN 12390-8: 2019).

Test	Al-WWS slag concrete	DS slag concrete	BA slag concrete	MA+M-DWS slag concrete
Water absorption	1.85%	2.00%	1.93%	1.85%
Water penetration	17 mm	11 mm	15 mm	13 mm

Example 9. Geotechnical Properties for Land Reclamation

The coefficient of consolidation of sludge-derived slag has been determined over a range of vertical stress (from 25 to 500 kPa).

Shear Strength Test and One-Dimensional Consolidation Tests

All slag samples underwent a direct shear test following the guidelines of BS 1377-7:1990. These tests were conducted using a direct shear test box with dimensions of 60 × 60 mm, and the average sample height was 22 mm. To assess the settlement characteristics of a structure or earthfill, both differential and total settlements, a one-dimensional consolidation test was performed in accordance with the specifications outlined in BS 1377-5:1990. The rate of consolidation was evaluated using the coefficient of consolidation, providing insights into the consolidation process.

Coefficient of Permeability

Coefficient of permeability of the sludge-derived slag were obtained via the falling head permeability test (KH. Head Vol 2). Under this test, a standpipe is connected to a sample. The volume of water that flows through the sample and the time taken is recorded and used to calculate the coefficient of permeability.

Angle of Shearing Resistance

The angle of shear resistance is the angle between the horizontal plane and the plane along which shear failure occurs in the material, which is the results for shear strength by direct shear - small shearbox apparatus.

Undrained Shear Strength

According to BS 1377:1990:Part 7:Clause 8, the undrained shear strength is obtained by subjecting the sample to both a constant confining pressure and strain controlled axial loading where the volume of the sample is kept constant.

Results and Discussions

The coefficient of consolidation of all sludge-derived slag decreased with the increase of the vertical stress present in FIG. 10, which is consistent with the results from previous studies on different land reclamation materials (Jain, A & Puri, N., *Proceedings of Indian Geotechnical Conference, 2013*, 22; Ding, G. et al., *Conservation and Recycling, 2019*, 150, 104428), indicating that the time required reaching a given degree of consolidation increases with the increase in effective stress. When vertical stress is applied to saturated soil, it compresses the particles and expels water, dissipating excess pore water pressure and causing consolidation. Increasing vertical stress increases effective stress, compressing soil particles and reducing void spaces, therefore limiting the water flow. This results in a lower coefficient of consolidation, slowing drainage and consolidation. Higher stress can alter soil fabric and structure, densifying the soil and restricting drainage paths, further hindering consolidation.

For vertical stress of 25 kPa, the coefficient of consolidation for the various sludge-derived slag varied from 6.6 to 39.1 m²/year. The difference between them decreased to 1.7 m²/year at the vertical stress of 500 kPa, indicating that effective stress is an important impact factor for consolidation. The consolidation coefficient of sludge-derived slag (1.6 - 39.1 m²/year) is lower than the sandy silt (72.5 m²/year) (Roggensack, W.D. *Geotechnical Properties of Fine-Grained Permafrost Soils*, 1977) but higher than clay (0.8 m²/year) (Morgenstern, N.R. & Smith, L.B., *Canadian Geotechnical Journal, 1973*, 10, 25), which could be attributed to the particle size distribution of sludge-derived slag in the range from clay to sand. Nevertheless, as the slag could be applied concurrently with the mixture of sand, silt, and clay (locally available or imported) during the actual land reclamation, the effects of the relatively lower consolidation coefficient of slag (or the relative longer reclamation duration expected) can be mitigated or minimized.

Table 26 lists the coefficient of permeability, angle of shearing resistance, and undrained shear strength of the sludge-derived slag. Coefficient of permeability quantifies the rate at which water can flow through the soil under a given hydraulic gradient. The coefficient of permeability of sludge-derived slag with 1.58×10^{-3} - 2.10×10^{-3} m/s was comparable to sand (from 1×10^{-4} to 1×10^{-2}) (Das, B.M. & Luo, Z. *Principles of Soil Dynamics*, Cengage Learning, 2016; Evirgen, B. *GEOMATE Journal*, **2015**, 8, 1283). The angle of shear resistance is the angle between the horizontal plane and the plane along which shear failure occurs in the material. Shear strength refers to the amount of shear stress a material can withstand before failure. These parameters provide important information on the ground-bearing capacity of the material. The angle of shearing resistance and undrained shear strength of sludge-derived slag were 36° - 42° and 316 – 438 kPa, comparable to the sand at 30° - 40° (Sezer, A. *Neural Computing and Applications*, **2013**, 22, 111) and 270 - 532 kPa (Bayat, E. & Bayat, M. *Arabian Journal of Geosciences*, **2013**, 6, 4409), respectively. The coefficient of permeability, angle of shearing resistance, and undrained shear strength of the sludge-derived slag were comparable to sands. These results indicated the sludge-derived slag could be considered as a promising alternative construction material suitable for land reclamation.

Table 26. Geotechnical properties of various sludge-derived slag.

Type	AI-WWS slag	DS slag	BA slag	MA+M-DWS slag
Coefficient of permeability (m/s)	2.09×10^{-3}	2.10×10^{-3}	2.05×10^{-3}	1.58×10^{-3}
Angle of shearing resistance ($^\circ$)	42	42	36	36
Undrained shear strength (kPa)	316	438	346	402

Example 10. Life Cycle Assessment (LCA) for Concrete Mortar and Land Reclamation

The life cycle assessment was carried out to evaluate the environmental impacts associated with the application of sludge-derived slag in comparison to sand.

Life Cycle Assessment (LCA)

This assessment was conducted using GaBi software and the Ecoinvent 3.5 database, which provided comprehensive data and modeling capabilities for calculating global warming potential (100 years) (GWP-100), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), and marine aquatic ecotoxicity potential (MAETP). By considering various relevant factors and parameters, the assessment aimed to quantify and

compare the use of sludge-derived slag versus sand to assess their respective environmental impacts. The functional unit was 1000 kg concrete or 1 m³ land reclamation material produced.

The boundary conditions for the application of sludge-derived slag and sand on concrete can be found in FIG. 11. The processes considered in this assessment consisted of the production of raw materials (i.e., sand, slag, cement, aggregate, and water) and transportation of materials. For simplicity, current LCA only considered the transport of sand overseas and excluded the transport of sand within the city as this was assumed to be comparable to the transport of slag generated in a city. It was also assumed that the transport of other materials (i.e., aggregate and cement) to be similar for both sand concrete and slag concrete. The process of slag generation from the co-gasification of wastes (MSW and sludge/ash) in the gasification plant (GP) was not considered in current LCA because the slag is considered as a by-product generated during the thermal treatment of wastes. For the land reclamation as illustrated in FIG. 12, the reclamation procedure was assumed to be the same for sand and slag because of the similar physical properties as observed. Therefore, only the production and transportation of sand were considered while slag was assumed to be a by-product generated within a city.

Results and Discussions

LCA was performed to evaluate the environmental impacts of using the sludge-derived slag as an alternative construction material for concrete production and land reclamation. The detailed comparison of environmental impact indicators between sand and slag concrete are shown in FIG. 13. Global warming potential (GWP) is one of the most important indicators for environmental evaluation, which measures the total amount of emissions of CO₂ from an activity or a product directly and indirectly over the life stages. GWP-100 for slag concrete production was 150.40 kg CO₂ eq., which was lower than 168.90 kg CO₂ eq. of sand concrete. This is because the slag was generated locally during the wastes treatment process while sand was excavated and imported from overseas. Notably, cement production contributed large amount of CO₂ for concrete production. For AP, slag concrete (0.33 kg SO₂ eq.) showed less than half of the result of sand concrete (0.81 kg SO₂ eq.). Slag concrete demonstrated superior performance in EP (0.09 kg Phosphate eq., 60.9% relative to sand concrete) and HTP (25.40 kg DCB eq., 65.2% relative to sand concrete) as well. Similar observation was found for MAETP, slag concrete has contributed to lower MAETP (42971.78 kg DCB eq., 77.7% relative to slag concrete).

Environmental impact indicators of reclamation by sand are listed in Table 27. The main difference between reclamation by sand and slag were the filling materials. With the

consideration of slag as a by-product of sludge gasification, which is conducted locally and avoids overseas transport, while sand was excavated and imported, relative impacts of reclamation by slag could be considered as negligible. It is obvious that all indicators including GWP-100 (99.41 kg CO₂ eq.) and AP (1.93 kg SO₂ eq.), EP (0.43 kg Phosphate eq.), HTP (127.84 kg DCB eq.) and MAETP (145909.90 kg DCB eq.) of reclamation by sand were significant. Slag is a by-product resulting from the high temperature slagging gasification process, whereas sand is obtained through conventional mining practices that follow the linear approach of "take-make-waste". By using slag instead of sand, the environmental benefits of transforming waste into valuable resources is showcased, in contrast to the extraction of natural resources through mining. This shift highlights the benefits of sustainable practices and the circular economy, where waste materials are repurposed, reducing the need for resource extraction and minimizing environmental impacts.

Table 27. LCA of land reclamation by using the imported natural sand.

Impact categories	Unit	Total	Sand (production)	Transport (ship)
GWP	kg CO ₂ eq.	99.41	62.5	36.91
AP	kg SO ₂ eq.	1.93	1.16	0.77
EP	kg Phosphate eq.	0.43	0.34	0.09
HTP	kg DCB eq.	127.84	108.66	19.18
MAETP	kg DCB eq.	145909.90	129400.54	16509.36

Claims

1. A method of providing a particulate slag suitable for use to replace sand or fine aggregates in a concrete, the method comprising the steps of:
 - (a) feeding a municipal solid waste and one or more of a wastewater sludge, a freshwater sludge and a sludge incineration ash through a top portion of a gasifier; and
 - (b) collecting a molten slag formed from the municipal solid waste and one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash from a slag collection outlet of the gasifier, quenching the molten slag to form granules and removing at least some diamagnetic metal particles from the slag to provide a slag suitable for using to replace sand or fine aggregates in a concrete, wherein:
 - the weight to weight ratio of the municipal solid waste to one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash is from 10:1 to 1:2; and
 - a bottom section of the gasifier is operated at a temperature of from 1,200 to 2,500 °C.
2. The method according to Claim 1, wherein the temperature of the bottom section of the gasifier is from 1,300 to 2,200 °C, such as from 1,500 to 2,000 °C, such as about 1,600 °C.
3. The method according to Claim 1 or Claim 2, wherein the weight to weight ratio of the municipal solid waste to one or more of the wastewater sludge, the freshwater sludge and the sludge incineration ash is from 9:1 to 1:1, such as 3.17:1 to 2:1.
4. The method according to any one of the preceding claims, wherein the wastewater sludge, the freshwater sludge and the sludge incineration ash is selected from one or more of the group consisting of a dewatered alum sludge, a dried sludge from a wastewater treatment facility, bottom ash particles formed from incineration of a sludge, and sludge incineration fine ash particles.
5. The method according to any one of the preceding claims, wherein the loading rate for the municipal solid waste is from 200 to 500±110 kg/h, such as from 222 to 428±108 kg/h and the loading rate of the one or more of the wastewater sludge, freshwater sludge and the sludge incineration ash may be commensurate with the weight:weight ratios described in Claim 1 or Claim 3.
6. The method according to any one of the preceding claims, wherein the total loading rate for one or more of the wastewater sludge, the freshwater sludge and the sludge

incineration ash is from 40 to 250 ± 60 kg/h, such as from 42 to 217 ± 60 kg/h and the loading rate of the municipal solid waste is commensurate with the weight:weight ratios described in Claim 1 or Claim 3.

7. The method according to any one of the preceding claims, wherein the apparatus used in the method further comprises a combustion chamber, a boiler, a cyclone, a gas cooling tower and a bag filter, which are fluidly linked in series in order to process a syngas produced by feeding both of the municipal solid waste and one or both of the wastewater sludge and a sludge incineration ash into the gasifier.

8. A particulate slag suitable for use to replace sand or fine aggregates in a concrete, the slag's elemental composition comprising each of Ca, Si, Al, Na, Fe, Mg, P, K, Ti, and Mn in an amount greater than 1g/kg.

9. The particulate slag according to Claim 8, wherein the slag has one or more properties selected from:

- (i) a mean particle size diameter that is less than 40 mm, optionally wherein the mean particle size diameter is from 1 to 5 mm, such as from 2.0 to 3.1 mm;
- (ii) the water absorption of the slag is from 0.5 to 0.7%, such as about 0.64%;
- (iii) the specific gravity of the slag is from 2.6 to 2.9, such as from 2.72 to 2.8;
- (iv) the bulk density of the slag is from 1.2 to 1.6 g/cm³, such as from 1.31 to 1.51 g/cm³;
- (v) the particle density of the slag on an oven-dried basis is from 2.5 to 3.0 g/cm³, such as from 2.74 to 2.80 g/cm³.

10. The particulate slag according to Claim 9, wherein the slag has all of the properties listed in (i) to (v) of Claim 9.

11. The particulate slag according to any one of Claims 8 to 10, wherein the particulate slag has angular to sub-angular morphology.

12. The particulate slag according to any one of Claims 8 to 11, wherein the particulate slag is in an amorphous solid form.

13. A mortar comprising:

- a particulate slag according to any one of Claims 8 to 12, or a particulate slag obtainable from a method according to any one of Claims 1 to 7; and
- a cement.

14. A concrete comprising:
- a particulate slag according to any one of Claims 8 to 12, or a particulate slag obtainable from a method according to any one of Claims 1 to 7;
 - a cement;
 - an admixture; and
 - coarse aggregates.
15. The concrete according to Claim 14, wherein the concrete has one or more of the following properties:
- (ia) a water absorption of from 1.85 to 2.00%;
 - (ib) a resistance to chloride ingress, once cured, of from 1379 to 1877 coulombs;
 - (ic) a compressive strength comparable to a concrete of Claim 14 made using sand instead of the particulate slag.

A set of well-engineered and predictable concrete products produced of co-gasification sludge-derived slag with the properties of:

- a. Low environmental impact green concrete (eliminates the need for excavation of natural sand).
- b. Low water absorption (1.85 to 2.00%).
- c. High resistance to chloride ingress (1379 to 1877 coulombs with grading identified as low) and good durability.
- d. Comparable compressive strength to typical sand concrete and potentially applicable for both non-structural and structural applications.