Alkali-activated binders – a sustainable alternative to OPC for stabilization and solidification of polluting fly ash from municipal solid waste incineration

Claudia Labianca[1], Carmen Ferrara[2], Yuying Zhang[1], Xiaohong Zhu[1], Giovanni De Feo[2], S.C Hsu[1], Siming You[3], Longbin Huang[4], Daniel C.W. Tsang[1,4*]

[1]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

[2] Department of Industrial Engineering (DIIN), University of Salerno, via Giovanni Paolo II, 132–84084 Fisciano, Italy

[3] University of Glasgow, James Watt School of Engineering, Glasgow, G12 8QQ, UK

[4] Sustainable Minerals Institute of University of Queensland, St Lucia QLD 4072, Australia

[*] Corresponding author: dan.tsang@polyu.edu.hk

Abstract

This research aims to evaluate the sustainability of alkali-activated binders for the stabilization/solidification (S/S) of municipal solid waste incineration fly ash (MSWI FA). A detailed environmental assessment of different alkali-activated mixtures was conducted using life cycle assessment (LCA) to identify the factors affecting their environmental burden. Ground granulated blast-furnace slag (GGBS) and metakaolin (MK) were used as the precursors. Results showed that all the alkali-activated blocks fulfilled the requirements for landfill and reuse as fill materials. Adopting alkali activation for S/S of MSWI FA instead of OPC allowed up to 70% reduction of global warming potential. However, in other impact categories such as human toxicity and land use, the alkali mixtures recorded higher values than the mix with OPC (+60-70%), primarily because of the impacts related to the production of chemical activators. The sensitivity analysis demonstrated that alternative production methods for sodium silicate and sodium hydroxide could enormously reduce the impacts related to the alkali solution. When the hydrothermal method for sodium silicate and the ODC method for sodium hydroxide were adopted, a reduction of 71%, 22%, and 24% was recorded in global warming potential, fossil resourse scarcity, and human toxicity categories, respectively, compared with the mix with OPC. Therefore, this study sheds light on alkali-activated materials as sustainable S/S alternative to OPC to promote carbon neutrality.

Keywords: clinker-free treatment; Low carbon binder; Supplementary cementitious materials; Hazardous waste management; Sustainable remediation; Incineration ash.

List of abbreviations

AAMs = Alkali-activated materials

APC = Air pollution control

BA = Bottom ash

DP =Diaphragm

FE = Freshwater eutrophication

FEcotox = Freshwater ecotoxicity

FPMF = Fine particulate matter formation

FRS = Fossil resource scarcity

FU = Functional unit

GC = GEOPOLYMER CONCRETE

GGBS = Ground granulated blast-furnace slag

GWP = Global warming potential

IR = Ionizing radiation

HT = Human toxicity

IWMF = Integrated waste management facilities

LCA = Life cycle assessment

LCI = Life cycle inventory

LCIA= Life cycle impact assessment

LU = Land use

MC = Mercury

MEcotox = Marine ecotoxicity

ME = Marine eutrophication

MK = Metakaolin

MM = Membrane

MRS = Mineral resource scarcity

MSW = Municipal solid waste

MSWI FA = Municipal solid waste incineration fly ash

ODC = Oxygen depolarized cathode

OPC = Ordinary Portland cement

PCDD/Fs = dibenzo-p-dioxins and dibenzofurans

POF = Photochemical oxidant formation

PTES = Potentially toxic elements

SOD = Stratospheric ozone depletion

S/S = Stabilization and solidification

TA = Terrestrial acidification

TCLP = Toxicity characteristic leaching procedure

TEcotox = Terrestrial ecotoxicity

WU = Water use

1. Introduction

Urbanization has led to a rapid growth of municipal solid waste (MSW) production. In China, 235.1 million tonnes of MSW were generated in 2020, with approximately 62% of which were incinerated (China's Statistic Yearbook, 2020). Due to the forthcoming depletion of landfill sites, incineration is considered as a preferred waste-to-energy approach that reduces the MSW volume by 90% and improves the sustainability of waste management (Qiang et al., 2015; HK EPD, 2018). MSW incineration (MSWI) commonly produces two main by-products, namely MSWI bottom ash (BA) and MSWI fly ash (FA) (Zhang et al., 2021). In particular, MSWI FA contains a high level of potentially toxic elements (PTEs) (lead, cadmium, chromium, mercury, nickel, zinc etc.) and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) (Fan et al., 2018), which leads it to be a hazardous waste. MSWI FA is collected before and after the air pollution control (APC) system, and it accounts for about 3–15 wt.% of the original waste total mass (Fan et al., 2018; Zhang et al., 2021). It is estimated that millions of tonnes of MSWI FA are piled up in open landfills in China as a result of a lack of disposal companies, with subsequent risks to the ecosystem (Xue and Liu, 2021). Therefore, there has been growing concern regarding the adverse effects on human health and the environment resulting from the disposal of MSWI FA (Li et al., 2019a). In addition, MSWI FA chemical composition can extremely vary according not only to the type of incineration treatment, but also to geographical and seasonal information.

China has launched the first technical specification about the management of MSWI FA (HJ 1134, 2020) pollution control in August 2020. If well-treated, MSWI FA can be considered as one type of general waste and disposed in sanitary landfill, or even be used for other purposes (GB 34330, 2017). Although the recycling of this material has not yet been globally regulated, it is necessary to investigate sustainable alternatives for the MSWI FA disposal (GB 34330, 2017). Over the last few years, increasing attention has been paid to properly stabilize MSWI FA for significantly lowering associated environmental risks at the final disposal site. So far, the most widely accepted solution involves stabilization and solidification (S/S) with a variety of hydraulic binders, such as cement, lime, blast furnace slag, etc. (Chen et al., 2019a; De Gisi et al., 2020).

In the last 60 years, OPC-based S/S has been proven to be an economically efficient approach to immobilize toxic and harmful pollutants in MSWI FA, through encapsulation, fixation, or adsorption in hydration products resulting from chemical reactions between cement and water, such as calcium silicate hydrates (C-S-H) gel and ettringite (AFt), (Contessi et al., 2020). However, the durability of OPC-based S/S is significantly weakened by the poor compressive strength of matrix encaptulating large proportions of MSWI FA. It is known that the high chloride and sulfate contents in MSWI FA can adversely affect the strength and durability of the final blocks (Xu et al., 2019). Guo et al. (2021) demonstrated a low compatibility of OPC with oxyanions (e.g., AsO_3^{3-}) or amphoteric metal ions (e.g., Zn^{2+}, ZnO_2^{2-}), due to a significant inhibition of the cement hydration caused by complexation reactions of calcium ions. Although this weakness may be improved by increasing the proportion of OPC in the mix, it will lead to the use of large amounts of cements and associated high costs. In addition, the production of OPC creates tremendously high carbon footprint (0.66–0.82 t CO_2 per t OPC) (Dung and Unluer, 2017), leading to a growing interest in alternative low-carbon binders. For each tonne of Portland cement produced, approximately 1 kg of SO_2, 2 kg of NO_x, and 10 kg of dust are emitted (Singh et al., 2020). Among alternative binders, alkali-activated materials (AAMs) have received increasing attention in recent years, especially for the possibility of recycling by-product or waste materials from agricultural and industrial processes, but also for their considerable chemo-mechanical performances. Jin et al. (2016) found that MSWI FA S/S based on the use of metakaolin (MK) displayed excellent stability in acid and alkaline environments and good performance as a building material with no secondary pollution. By entrapping several components, such activation creates a cement-like matrix that drastically reduces pollutant mobility. Furthermore, AAMs can guarantee a higher mechanical resistance than traditional concrete (Chindaprasirt and Rattanasak, 2018). It has been suggested that the properties of MK-based AAMs can be improved using other thermally activated clays with higher Si/Al ratios or by combining with slag acting as a Ca-rich precursor (Davidovits, 2009). Precursors derived from industrial and agricultural wastes may be used to lower the costs and assist the waste disposal for sourcing process, such as ground granulated blast furnace slag (GGBS), pulverized fuel ash, glass powder, palm oil fuel ash, rice husk ash, silica fume, and marble powder rich in aluminate-silicate content. These wastes have been found to have a big potential in S/S application via alkali-activation (Jeremiah et al., 2021). However, the relative abundance of different waste varies, such as the limited availability if GGBS as a by-product of the manufacture of pig iron from iron ore (Davidovits, 2009; Juenger et al., 2019). Other industrial wastes and by-products (such as rice husk ash, silica fume, sodium aluminate slurry) have great potential as sustainable activators in AAMs (Billong et al., 2021). Therefore, the development of alternative materials or optimized binary mix designs must consider the availability of wastes and their sources.

Evidence suggests that AAMs yield the best CO_2 reduction as of 26−45% compared to normal OPC (Krivenko, 2017). McLellan et al. (2011) demonstrated that AAMs could significantly reduce CO_2 emissions by up to 64% over OPC-based concrete. In a more recent study, the global warming potential (100-years) of AAMs was 5–35% lower than PC concrete (Patrisia et al., 2022). Nonetheless, there is some concern about the impacts related to the activator solution used in the geopolymerization process, which are usually made as a combination of silicates, hydroxides, and carbonates (Krivenko, 2017). Salas et al. (2018) identified sodium hydroxide as the most relevant life cycle process in terms of carbon emissions, being used also for sodium silicate production. In the studies by Robayo-Salazar et al. (2018) and Bajpai et al. (2020) sodium silicate and sodium hydroxide contributed for 85% and 60% as total, respectively, of the total emissions despite representing less than 9% in volume of the alkali-activated concrete mixture. Sodium hydroxide and sodium silicate are the main constituents responsible for 60% of total environmental impacts of geopolymer concrete (GC).

Therefore, the identification of the optimal mix design has a key role for the evaluation of the life cycle assessment (LCA) of AAMs. The main strategy for a sustainable mix should focus on minimizing the consumption of energy or raw materials and the generation of waste.The objective of this study is to develop and identify the most sustainable alkali-activated mixture design to stabilize MSWI FA, alternatively to OPC. Firstly, an experimental phase allowed investigating the effectiveness and the compliance with the regulations of the S/S mix designs under study. Then, a LCA-based evaluation explored the main impacts and identified the most environmentally sustainable design. Through the sensitivity analysis, a focus on alternative and more sustainable production methods for alkalis was essential. It is expected that the data presented in this paper will assist industry stakeholders and researchers in getting a comprehensive idea of the potential of using AAMs for MSWI FA S/S and spur environmental responsibility actions.

2. Method

This research contains three main phases, as shown in Fig. 1. Phase 1 includes the preparation and technical evaluation of different mixtures of alkali-activated S/S blocks, where the combination of two different precursors (GGBS and MK) is considered. In Phase 2, the environmental impacts of the S/S mix designs are evaluated and interpreted by employing LCA. Lastly, Phase 3 aims to identify the best mix design for sustainability and technical requirements.

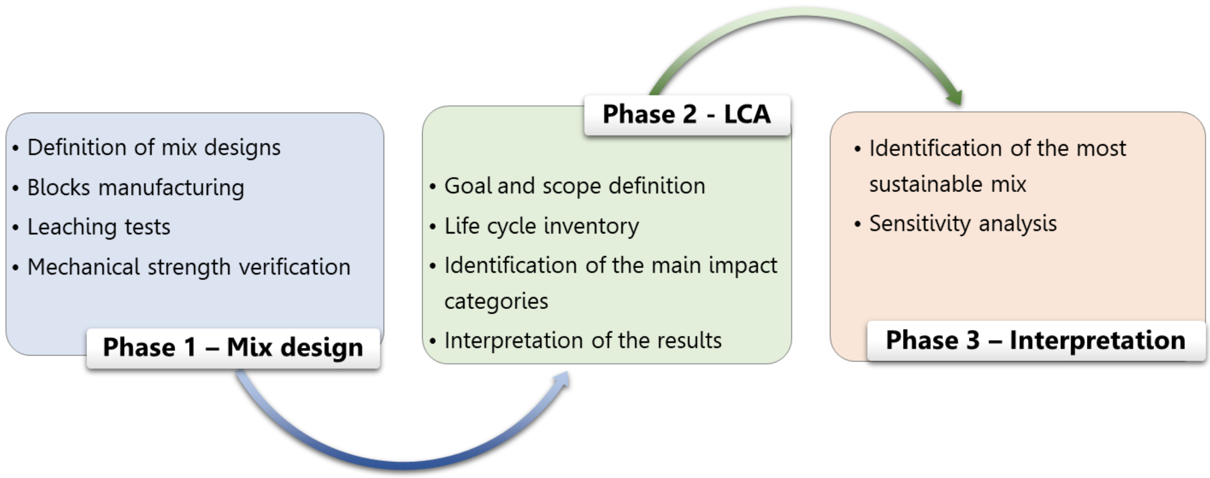

Figure 1. Flowchart of the methodology used in this study.

2.1 Materials and mix designs

The MSWI FA used in this study was collected from the incinerator in Shenzhen, China. GGBS and MK were used as the precursors, and sodium silicate and sodium hydroxide-based solutions were chosen as the activators. All the chemicals and binders used were purchased from Mainland China; instead, OPC was supplied by Green Island Cement Limited, Hong Kong. The chemical compositions of raw materials are reported in Table S1 (Supplementary Materials). Four different alkali mixtures were designed to investigate the efficiency and sustainability of alkali-activated S/S treatment, as shown in Table 1. A conventional case scenario with OPC was also considered as a comparison.

The alkali content and type are crucial for achieving satisfactory performance of AAMs, which depends significantly on the selection of the precursor (Wang et al., 2015). Normally, the aluminosilicate precursor with higher CaO content requires lower alkali content. For example, GGBS is a typical high-Ca precursor for preparing AAMs, which requires only 4-7 wt.% alkali content (R_2O eq.%) for strong alkalis (R stands for alkali metals) (Wang et al., 2015). However, MK needs more alkalis (> 10 (R_2O eq.) wt.% alkali content (Sun et al., 2020)) due to the lack of CaO (Rashad, 2013). If the water glass (i.e., sodium silicate, $R_2O{\cdot}(n)SiO_2$) is used for producing AAMs, a modulus (n) of 1.0-2.0 is normally chosen for the optimised properties (Li et al., 2019b; Provis et al., 2019). The suitable concentration of water glass (Ms = 1.0) is the alkali activator that we used in this study. Therefore, the alkali content in this study is proportionally designed based on those existing studies, i.e., 5~8 wt.% for GGBS and 10~13 wt.% for MK. In addition, a small amount of alkali (0 ~ 1 wt.%) was assigned to MSWI FA to activate the aluminosilicates contained in it to enhance the S/S efficiency. The MSWI FA content was fixed as 75 wt.% of the total solid binder in the mixtures, and the remaining 25 wt.% was either MK, GGBS, and OPC or the mixture of them (Table 1). Two binary systems were also considered with the GGBS:MK ratio equal to 9:1 and 7:3. The conventional S/S with OPC (M5) was designed according to Eq. 1 (Chen et al., 2022) for achieving a suitable workability of paste:

$$Water\ (wt.\%) = OPC\ (wt.\%) \times 0.4 + MSWI\ FA\ (wt.\%) \times 0.45 \qquad \text{Eq. 1}$$

Table 1. Mix design for S/S of MSWI FA (wt.%).

	Mix design	MSWI FA	GGBS	MK	Sodium silicate	Sodium hydroxide	OPC	Water
M1	**MSWI FA + GGBS**	51.55	17.18	-	1.22	0.77	-	27.49
M2	**MSWI FA + MK**	49.68	-	16.56	1.49	5.79	-	26.49
M3	**MSWI FA + GGBS + MK (9:1)**	51.36	15.41	1.71	3.29	0.84	-	27.39
M4	**MSWI FA + GGBS + MK (7:3)**	50.97	11.89	5.10	3.86	0.99	-	27.18

M5	**MSWI FA + OPC**	52.17	-	-	-	-	17.39	30.43

2.2 Samples preparation and characterization

The block production process involved solution preparation, dry and wet mixing of powders, casting, and curing phases. In the mixing phase, binders and MSWI FA were dry-mixed for 2 min, and then the activator solutions were added for another 3-min mixing to obtain a homogeneous paste. In the casting phase, fresh alkali-activated pastes were poured into 20 x 20 x 20 mm steel molds. All samples were demolded after 2 days, wrapped in a waterproof membrane, and kept at 23 ± 2 °C in a curing chamber for up to 28 days and 60 days. All the experiments on S/S blocks were in triplicates for quality assurance. The 28-d and 60-d uniaxial compressive strength of the S/S blocks was tested using a universal testing machine (Testometric CXM 500-50 KN) and the loading rate was 0.5 mm s^{-1} according to BS EN 12390-3 (2019). The leachability of PTEs together with the pH was tested according to the Toxicity Characteristic Leaching Procedure (TCLP) (US EPA, 2019). The leaching concentrations of PTEs were detected by inductively coupled plasma atomic emission spectrometry (ICP-AES, Spectro Arcos). Further details of the procedure can be found in Wang et al. (2019).

2.3 LCA study

2.3.1 Goal and scope

The goal of the study was to comparatively evaluate the environmental life cycle impacts associated with the different S/S mix designs for MSWI FA treatment defined in Section 2.1 to identify the most environmentally sustainable alternative. Following the guidelines provided by ISO 14040 (ISO, 2006), the LCA was performed according to a cradle-to-gate approach. The new Integrated Waste Management Facilities (IWMF) constructed in Hong Kong on an artificial island near Shek Kwu Chau were considered as the case study (HK EPD, 2022). The boundaries for the system included the raw materials extraction, processing, transport, and the S/S block production (Fig. 2) for all the scenarios considered. The end-of-life was not included in this study being similar for all the scenarios. In agreement with other LCA studies on the topic, the functional unit of the study was defined as 1 m^3 of final product containing MSWI FA (Colangelo et al., 2021; Hossain et al., 2021) as it is more representative. An averaged density (Table S2) was considered to facilitate data management and application as all the mixes had similar density values (Colangelo et al., 2021). Furthermore, it should be noted that the different types of S/S mixtures had comparable mechanical properties, workability, and durability performance and they all accomplished the standard technical requirements for on-site landfill use as fill materials (HK EPD, 2011).

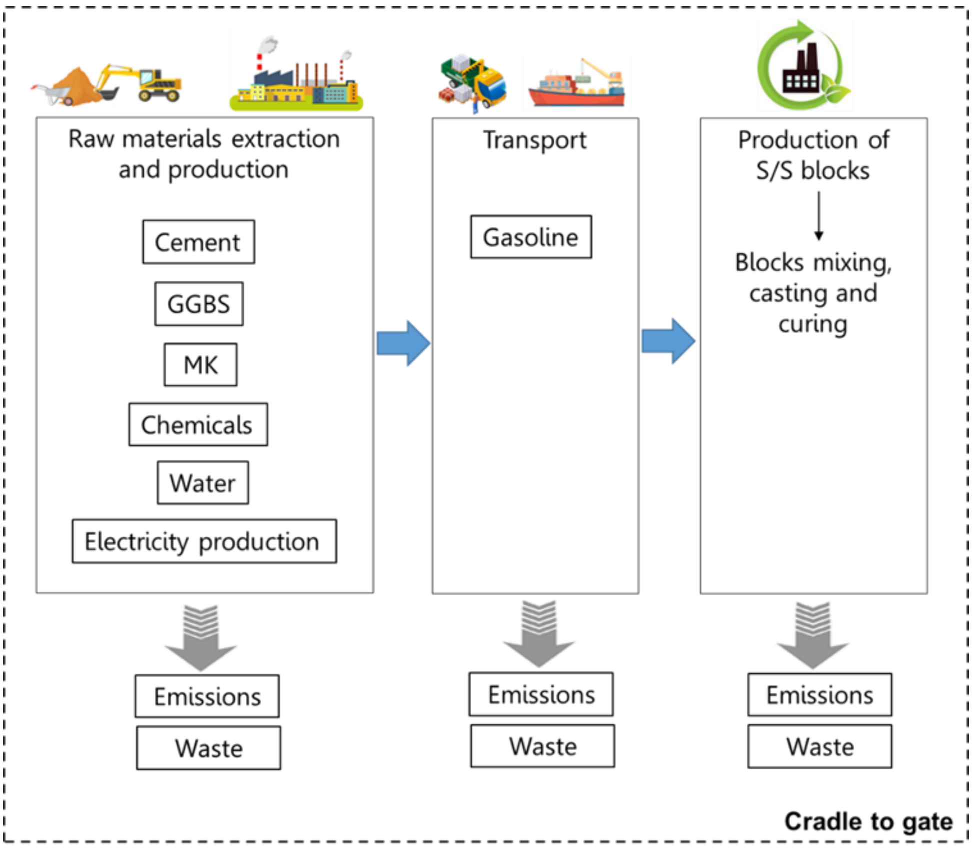

Figure 2. System boundaries of the studied S/S blocks.

2.3.2 Life cycle inventory

For this LCA step, all relevant aspects of energy and mass flow, as well as emissions to air, water and land were collected for each unit process and normalized to the functional unit of the study. The modeling of the proposed AAMs- and conventional cement-based S/S treatments was performed using the SimaPro® software v. 9.0049 to model products and processes comprehensively and analyze the results interactively (PRé Consultants, 2019). All the data considered for the material and energy flows were obtained from both laboratory analyses (primary data) and Ecoinvent v. 3.3 database or scientific literature (secondary data). In particular, secondary data were considered for the upstream flows, from the extraction of raw materials to their processing phase, and primary data were used for the production of S/S blocks. To ensure regionally specific results, local data were used to the maximum extent possible.

The weight values of all components contained in each MSWI FA S/S block can be obtained from the data reported in Table 1, considering the total weight of the blocks (Table S2). A variety of materials along with their processing and transport are required for the comprehensive assessment of all scenarios. Considering Hong Kong's limited resources, construction materials are mainly imported from Mainland China or other countries (Hossain et al., 2019). For all the scenarios, the transport distances were calculated from each material production site to the block manufacturing location in Hong Kong. A preliminary screening of possible suppliers showed several available options in the Guangdong province from where all the required materials can be shipped by barge to the artificial island where the new IWMF in Hong Kong is located. Table 2 lists the imported materials as well as their distances and modes of transport. Table 3 shows the amount of energy consumed during S/S block production. GGBS is a by-product of iron making; however, in Ecoinvent database v. 3.3 the entire production process of GGBS is available with all emissions and resources included. For MK, the database Ecoinvent was used jointly with literature data (Habert and Ouellet-Plamondon, 2016). MSWI FA was considered to be burden-free since the objective of the study was to identify the best mix design to stabilize MSWI FA and no avoided impacts of landfill disposal were considered.

Table 2. Distances and modes of transport used in this study.

Materials	Imported from	Transport type (t)	Distance
GGBS	Zhanjiang, Guangdong Province, Maoming port, China	Inland waterways barge	240 NM
MK	Maoming port, Guangdong Province, China	Inland waterways barge	180 NM
OPC	Local supplier in Hong Kong	- Lorry (16-32 t)	27 km
		- Inland waterways barge	13 NM
Sodium hydroxide	Canton, Guangdong Province, China	Inland waterways barge with reefer machine	75 NM
Sodium silicate	Sanshui Foshan, Guangdong Province, China	Inland waterways barge with reefer machine	100 NM

Table 3. Materials and energy requirements used in this study.

Material	Upstream data source
MSWI FA	Burden-free
GGBS	Ecoinvent
MK	Ecoinvent + Literature
OPC	Ecoinvent

Sodium hydroxide	Ecoinvent (Sodium hydroxide in 50% solution state, membrane cell)
Sodium silicate	Ecoinvent (Sodium silicate in 37% solution state)
Deionised Water	Ecoinvent
Lorry (16-32 t)	Ecoinvent
Lorry with refrigerator machine (7.5-16 t)	Ecoinvent
Inland barge	Ecoinvent
Inland barge with refrigerator machine	Ecoinvent
Electricity country mix	Ecoinvent (Electricity, medium voltage CN)
Heat	Ecoinvent
Processes	**Energy requirement**
AAMs Block making process	7 kWh (8 min mixing)
Solution preparation	6 kWh (4 h mixing)
OPC Block making process	5.5 kWh (6 min mixing)

2.3.3 Life Cycle Impact Assessment

The LCA analysis was performed using ReCiPe 2016 (H), in which the key issues were assessed from a hierarchical perspective based on midpoint (problem oriented) and endpoint (damage oriented) indicators (Huijbregts et al., 2017). There are 22 categories in the endpoint approach, which are classified into three macro-areas: Human health (measured in terms of disability adjusted life years, DALYs), Ecosystems (measured in terms of species × year), and Resources (measured in terms of USD 2013) (Huijbregts et al., 2017). Both levels of the method were used to assess the impacts, and the results describe both midpoint and endpoint indicators. However, the most representative midpoint categories were considered for further discussion. In such cases, only the categories that contributed the most to the endpoint level were chosen, as defined by Cleary (Cleary, 2013). In particular:

- Global warming potential (GWP, kg CO_2eq) that evaluates the integrated infrared radiative forcing increase of greenhouse gas (GHG).

- Particulate matter formation (PMF, kg PM2.5eq) that considers the air pollution that causes primary and secondary aerosols in the atmosphere.

- Fossil resource scarcity (FRS, kg oileq) that considers the fossil fuel potential, defined as the ratio between the higher heating value of a fossil resource and the energy content of crude oil.

- Land use (LU, m^2a) that focuses on the relative species loss due to local land transformation, land occupation, and land relaxation.

- Human toxicity (HT, kg 1,4-DBeq) that accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical.

- Water use (WU, m^3) that calculates the water consumed and not available anymore in the watershed for humans nor for ecosystems.

3. Results and discussion

3.1 Compressive strength and leachability

The density (Table S2) and compressive strength of the investigated pasteswere experimentally measured. A barely perceptible difference can be observed in the density of S/S blocks because MSWI FA accounts for 75 wt.% in the final matrix. Regarding the compressive strength of AAMs, all the blocks complied by far with the strength requirement (1 MPa) for on-site use as fill materials (HK EPD, 2011) (Fig. 3a). Compared to the mix with MK, the mix with GGBS performed better with an increase of 20% and 31% of the final compressive strength at 28 and 60 days, respectively. This can be allocated to the fact that in the calcium-containing binder, calcium silicate hydrate/calcium aluminosilicate hydrate (C-S-H/C-A-S-H) seeds can serve as nucleation sites to promote the formation of geopolymer gel (Yip and Van Deventer, 2003; Puligilla et al., 2019).

However, the combination of GGBS with MK in a 7:3 weight ratio developed final mechanical strength higher than single-binder mixes, in particular an increase of 21%, 45%, 20% than mix M1, M2, and M3 was recorded, respectively. Yet the compressive strength was higher than 10 MPa in all scenarios with peaks of 22.18 MPa and 17.46 MPa for M4 and M1, respectively. The mix M5 with 25% OPC showed a compressive strength at 28-d lower than the AAM blocks, particularly 61%, 51%, 66%, and 70% lower than M1, M2, M3, and M4, respectively. At 60-d this difference was even stronger, as it is shown in Fig. 3. This outcome was in line with the studies by Chen et al. (2019b; 2022) on OPC-based S/S and it underlines the great potential of geopolymerization technology for diverting hazardous wastes from disposal to reuse in engineering applications where a much higher mechanical strength can be reached (Hossain et al., 2020).

The immobilization efficiency must fulfill the leachability limits. At this regard, all the mixes complied not only with the "Landfill Disposal Criteria" (HK EPD, 2011) but also with the "Universal treatment standards for on-site reuse of cement stabilization/solidification treated soil" in Hong Kong (HK EPD, 2011) (Fig. 3b-c). The TCLP leachability results of untreated MSWI FA is shown in Table S3. The pH ranges from 8 to 11 for alkali-activated mixes, falling within the optimum 5–11 range proposed by Yakubu et al. (2018), as most PTEs can be effectively solidified/stabilized within this range. The mix with GGBS reached more alkaline pH values compared with MK, following the same trend also in the binary systems where mix M3 scored a higher value than mix M4 both at 28-d and 60-d.

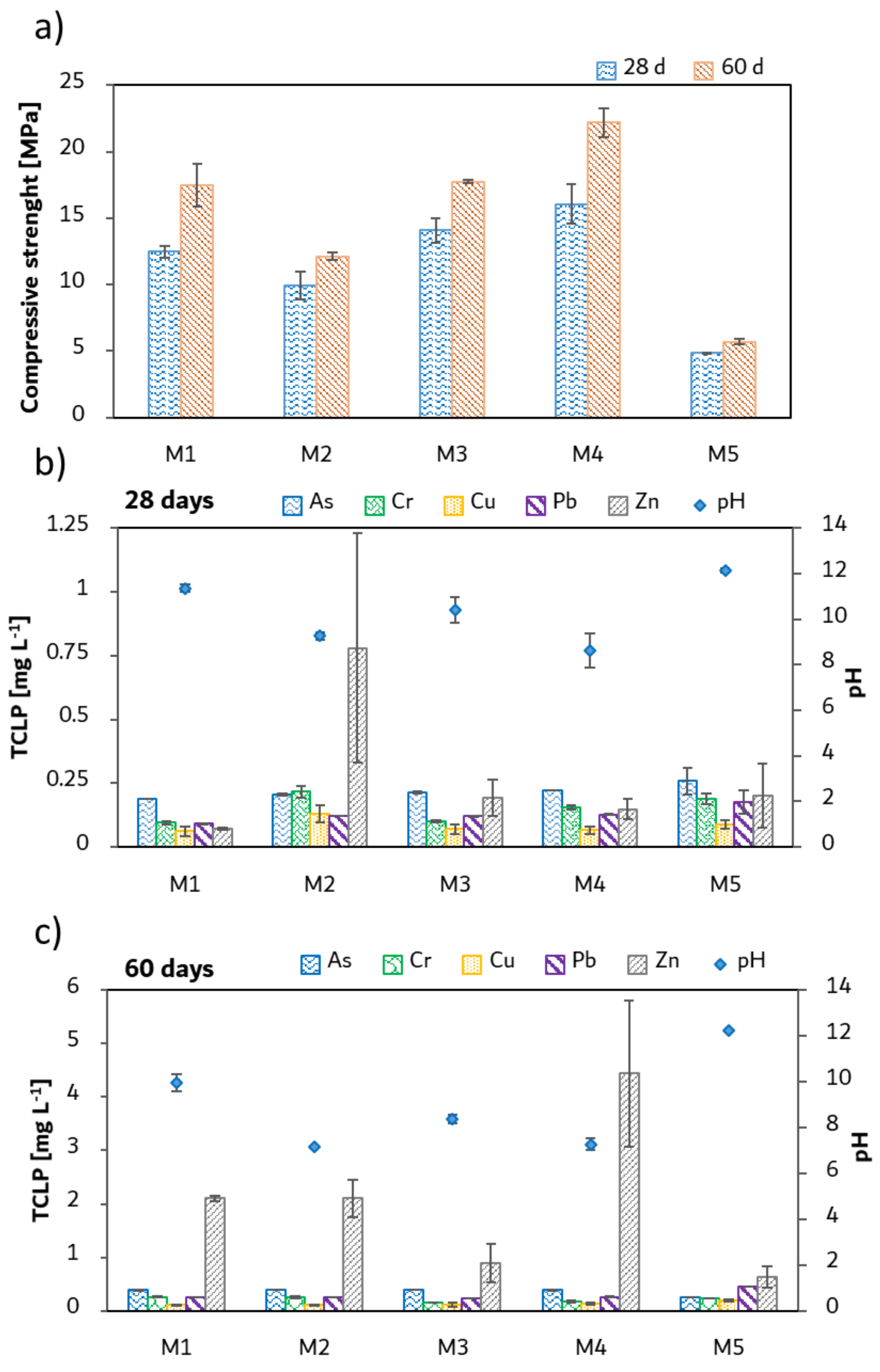

Figure 3. (a) Compressive strength of MSWI FA S/S blocks at 28 and 60 days and TCLP leachability of MSWI FA S/S blocks at (b) 28 and (c) 60 days (Leachability limits of trace elements: 5 mg $^{-1}$ of As, 0.6 mg L^{-1} of Cr, 0.2 mg $^{-1}$ of Cu, 0.75 mg L^{-1} of Pb, 4.3 mg $^{-1}$ Zn) (HK EPD, 2011).

As a result of the presence of aluminosilicate hydrates, AAMs reached a higher compressive strength compared to the conventional scenario with OPC. This outcome demonstrates the great potential of recycling MSWI FA into construction materials. However, field applications of waste-derived AAMs are rare due to insufficient standards and guidelines.

3.2 LCA results

The life cycle impacts of the considered MSWI FA S/S blocks are shown in Figs. 4a-b and Table S4. The values are reported in percentage terms, normalized to the highest impact value obtained for each category. In all the three endpoint categories (Fig. 4a), the mix M2 with MK showed the highest impacts. The mix M1 with GGBS reached approximately comparable values of the binary system M3, while the binary scenario M4 recorded higher impacts due to a larger quantity of MK in the mix design. The conventional mix with OPC recorded the highest impacts on human health and ecosystems categories but lower impacts on resources scarcity, where instead mix M2 with MK scored the maximum.

From Fig. 4b, it is interesting to highlight that mix M1 with GGBS used as the precursor reached the lowest impact values in various categories among all mixes. However, the mix with OPC recorded comparable or even lower values in most categories, except for the impacts on climate change, which were extremely high and equal to 292 kg CO_2eq (Table S4). Compared to the traditional cement binder, a reduction of 60% in CO_2 emissions was obtained with mix M1. This is in line with other LCA studies that estimated a reduction in GHGs between 40% and 75% for AAMs (Bianco et al., 2021; Colangelo et al., 2021). Instead, mix M2 represented the worst scenario in almost all the midpoint categories. This is ascribed to the energy-intensive calcination process for metakaolin production (Habert and Ouellet-Plamondon, 2016) usually in a temperature range of 500–950°C (Cheng et al., 2019). This agrees with the output by

Colangelo et al. (2021), where the scenario with MK produced three times the impacts related to the mix with GGBS in terms of GWP. It is noteworthy that the impacts on the category FRS at the midpoint level and Resources at the endpoint one are much lower for the conventional scenario with OPC, highlighting a non-correlation with climate change, despite the consumption of fossil resources accounted in the GWP. In fact, among all the emissions to air related to the clinker production process, which is included in the cement production, 0.84 kg of fossil carbon dioxide and 0.015 kg of biogenic carbon dioxide are emitted from every kg of produced clinker (Ecoinvent, 2016). Carbon dioxide released from cement manufacturing is mainly caused by the calcining process (removing CO_2 from limestone to form clinker) accounted for the 90% of the total CO_2eq, while the remaining is released during the burning of fuel in the kilns and other manufacturing processes (Huntzinger and Eatmon, 2009), as shown in the tree structure exported from SimaPro and presented in Figs. S3 and S6 in the Supplementary Materials.

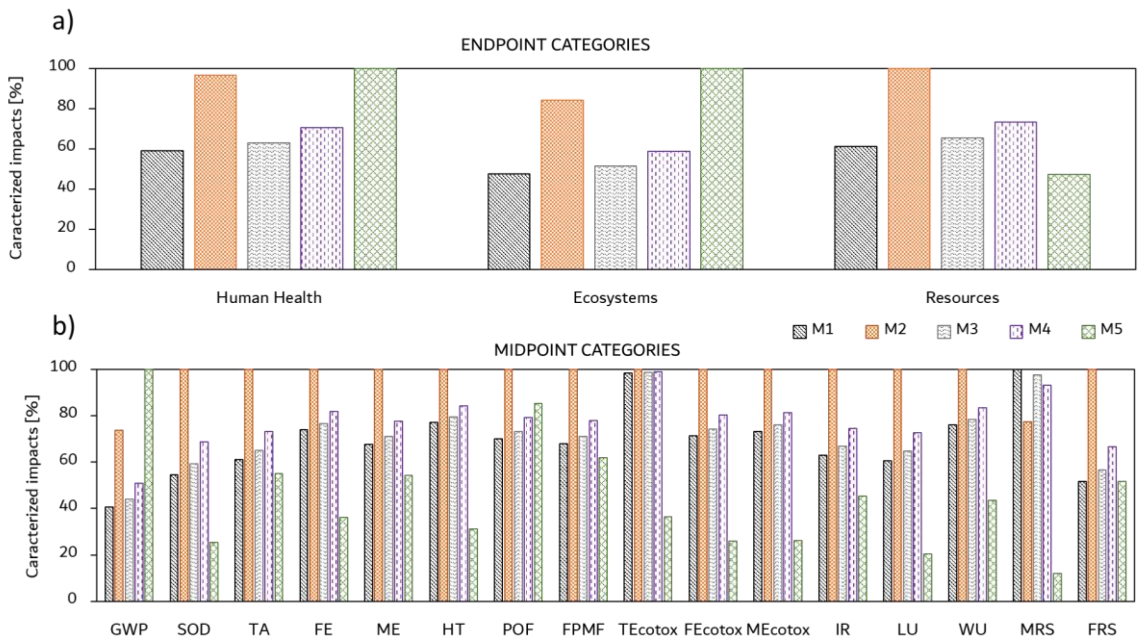

Figure 4. Comparison of the environmental impacts in percentage of MSWI FA S/S blocks estimated with the (a) endpoint and (b) midpoint categories of ReCiPe 2016.

Figure 5 shows a contribution analysis with the most relevant midpoint categories with the scope to identify each design's components responsible for the highest impacts. For all the considered midpoint categories, the chemicals (sodium hydroxide and sodium silicate) provided the highest contributions (always greater than 50%) to the total impacts of all mixes, except for mix M5. It is evident that the tremendously high impact is related to the alkali solution used in the AAMs, but particularly to water glass (Figs. S1, S2, S4, and S5). MK recorded the highest contribution in GWP and FRS categories, underlining the footprint of the calcination process (Figs. S2 and S5). GGBS contribution falls within the range 15–35%, with the highest value in the HT category. Regarding mix M5, OPC production is the critical factor responsible for the highest contributions to the total impacts. The electricity related to the solution and paste mixing provided low contributions to the total impacts of all mixes, but the highest percentage value was found for the category GWP, where mix M1 accounts for 10% of the total. Also transport recorded low impacts for all categories, with the highest contribution of 8% of the FRS in scenario M1. Using barges as the primary means of transport is highly recommended, mainly because the average cargo capacity of a barge is generally 15 times greater than one rail car and 60 times greater than one semi-trailer (Dry Cargo International, 2022). Size is the key to water transportation's efficiency, and it represents a real green alternative to trucking. Lastly, the water consumption was higher in mix M5 where a higher amount of water was used for mixing the paste, compared to scenarios M1, M2, M3, and M4 where an alkaline solution was required.

In line with Habert et al. (2011), this study highlights that the production of alkali-activated blocks has more significant impacts on the midpoint categories than OPC-based blocks, except for the GWP category. Other studies have reported similar concerns about the effects related to sodium silicate production (Dal Pozzo et al., 2019). Although the highest impacts in most of the categories are related to the chemicals used in the alkali solution, a properly-planned mix design can help reduce the quantity of sodium silicate and sodium hydroxide necessary to activate the precursors in the alkali-activated S/S treatment. In fact, according to the type of aluminosilicate precursor, the higher the CaO content in the raw material, the less alkali-activating solution is required. Therefore, GGBS is more sustainable compared to MK being richer in CaO content (Wang et al., 2015). The low Si/Al ratio in MK-based AAMs means a higher quantity of sodium silicate and water are required, leading to higher environmental impacts (Juenger et al., 2019). Another research approach could be to use particle technology more effectively, as proposed in the cement industry (Habert et al., 2011). Increasing particle packing in the AAM mix would result in greater packing, requiring less active binder and alkali solution (Provis et al., 2010).

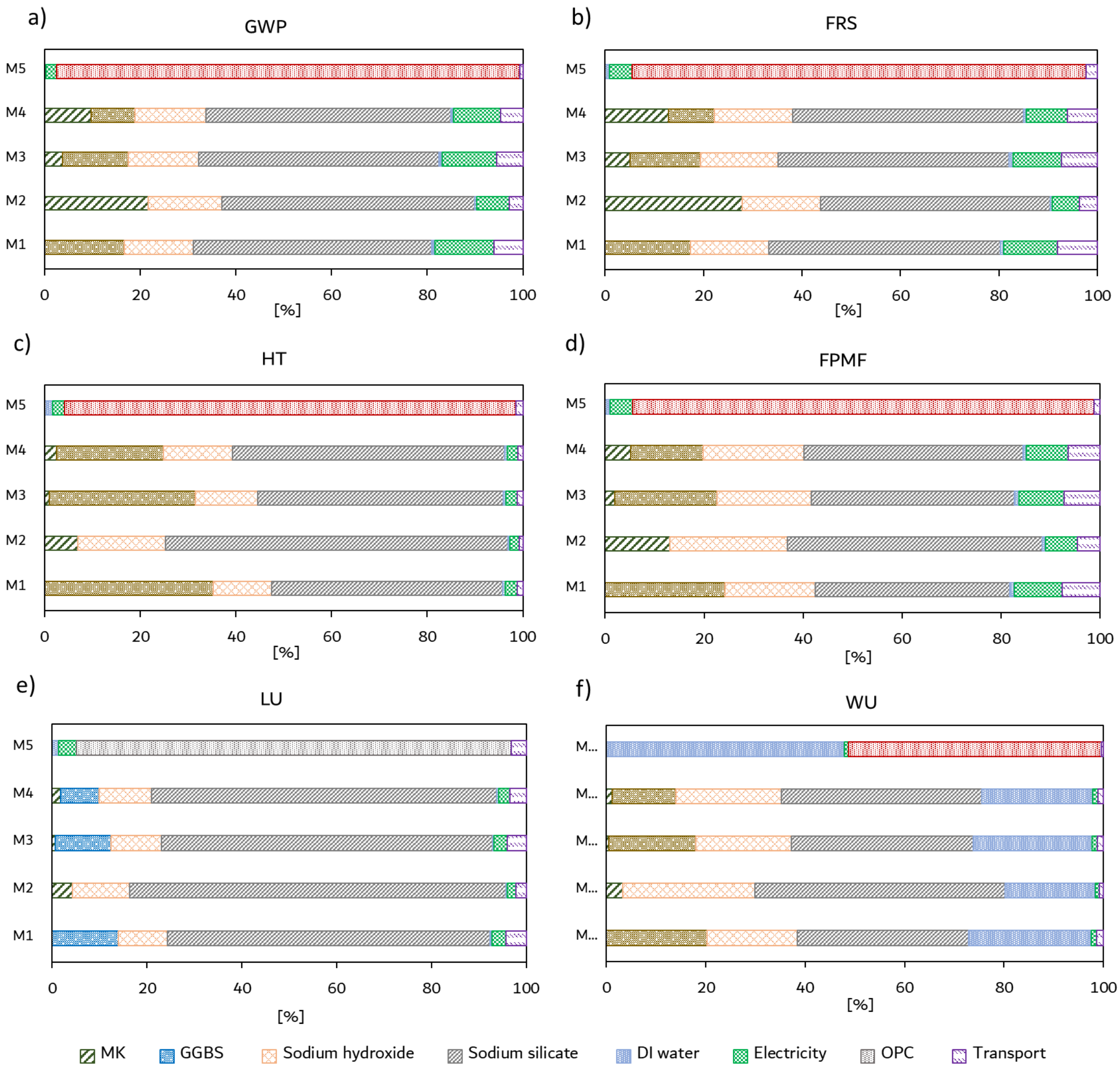

Figure 5. Contribution analysis that all components provided to the total impacts of each mix, estimated with the midpoint impact categories: (a) Global warming potential, (b) Fossil resource scarcity, (c) Human toxicity, (d) Fine particulate matter formation, (e) Land use, and (f) Water use.

4. Sensitivity analysis

Chemicals significantly influenced the results of alkali-activated blocks, as shown in Section 3.2. About 64–68% of the total GHGs emissions for block production are associated with sodium silicate and sodium hydroxide (Fig. 5a). A sensitivity analysis thus plays an essential role in estimating uncertainty and strengthening the reliability of the obtained results when using different LCI input data for chemicals.

A sensitivity analysis following a one-at-a-time approach was carried out by varying chemical production processes. A two-at-a-time approach was also included to identify the best combination of production methods. Sodium silicate can be manufactured via furnace or hydrothermal routes (Trabzuni et al., 2011). Regarding sodium hydroxide, three main different production methods have been usually adopted worldwide: (i) membrane (MM), (ii) diaphragm (DP), and (iii) mercury (MC) -based technologies. The membrane process is the most used and has undoubtedly replaced MC and DP methods. An innovative version of the MM technology is Oxygen Depolarized Cathode (ODC), and it represents a promising approach for reducing the electricity demand (Jung et al., 2014). Further details about the above-mentioned production systems can be found in Section 5.

In this sensitivity analysis, alternative production scenarios were considered for both sodium silicate ((i) 37% as base scenario, (ii) 48% as alternative route) and sodium hydroxide ((i) MM as base scenario, (ii) DP as an alternative, (iii) ODC as an alternative). Mix M1 was used as the base scenario since it represents the best alternative from the LCA study. It included sodium silicate at a solution of 37% solid and sodium hydroxide produced via the MM production route. In all the above-mentioned scenarios, Ecoinvent was used as the database for LCI-data except for ODC chlor-alkali electrolysis, which is not globally available at a large scale yet. In this last case, the study by Jung et al. (2014) was considered as reference, and a mass allocation was used to define the environmental impacts associated with NaOH production. Table S5 shows the sensitivity analysis outcomes where the percentage difference for each midpoint category was calculated in reference to the base scenario mix M1.

It is noteworthy that when sodium silicate is produced via the hydrothermal liquor route, almost all the midpoint impacts decrease, with a reduction equal to -17%, -6.5%, -52%, -7% for GWP, FRS, LU, HT, respectively (Fig. 6). However, WU recorded an increase of 16% compared to the base scenario with the furnace liquor route. Regarding sodium hydroxide, the DP method recorded slightly higher values than the base scenario, in a range of 0-2%, with a unique peak of around +17% for WU category. The new innovative production route ODC-based recorded the best results with a reduction of all the impacts, particularly -40%, -27%, -23%, respectively for GWP, FRS, and HT of the base scenario with GGBS. In a direct comparison with mix M5 with OPC from Section 3.2, the scenario M1 48% - ODC, where two parameters have been varied at the same time, can reduce the total GWP, FRS, and HT of -71%, -22%, and -24%, respectively. These outcomes are novel and for the first time AAMs recorded better results not only in GWP category but also in FRS and HT. This sheds light on the great value of AAMs for the MSWI FA S/S treatment and underlines the importance of the production cycles of raw materials.

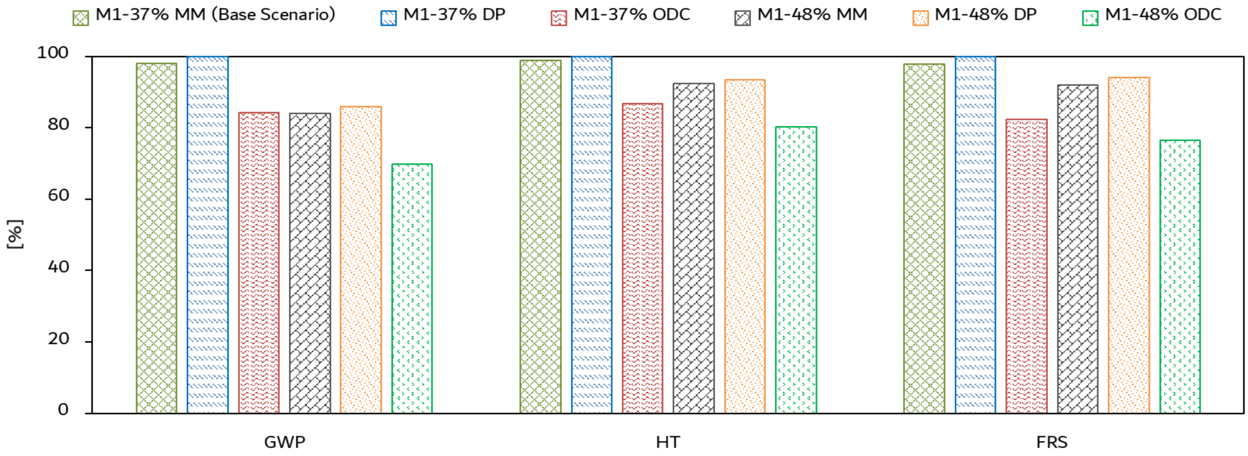

Figure 6. Sensitivity analysis for alternative production scenarios for sodium silicate and sodium hydroxide for GWP, HT, and FRS midpoint categories.

5. Alternative production methods for alkalis

In order to achieve net-zero emissions by 2060 (Shi et al., 2021), the global goal is to create a decarbonized society as soon as possible, so that anthropogenic emissions (sources) and removals (sinks) of GHG can be balanced out (global carbon neutrality). Therefore, the choice of the best mix design and materials is a crucial step when evaluating a S/S treatment.

As described in Section 4, sodium silicate can be manufactured via furnace or hydrothermal route (Figs. 7a-b). In the furnace process, silicon sand and soda are melted at a temperature range of 1100–1200 °C to produce water glass directly, resulting in a high SiO_2/Na_2O molar ratio, and usually made available as an aqueous solution at ~37 wt.% (Passuello et al., 2017). Instead, in the hydrothermal process, an autoclave is used to dissolve sand in sodium hydroxide solution at 180-300°C resulting in sodium silicate with a lower SiO_2/Na_2O molar ratio and made available as a ~48 wt.% solution (Trabzuni et al., 2011). The energy consumption for furnace lumps dissolving and filtering in Ecoinvent is estimated to be 0.996 MJ/kg and 0.007

kWh/kg. This is slightly higher than the range 0.345-0.920 MJ/kg suggested by Fawer et al. (1999). The second route involves hydrothermally dissolving silica sand in sodium hydroxide solution. Reactions are conducted inside autoclaves, which are especially designed to handle aggressive conditions. Upon filtering, a sodium silicate solution with a solid content of 48% is obtained. In this case, 0.732 MJ/kg and 0.019 kWh/kg of output product are associated to this production route in the database, falling in the range 0.350-0.680 MJ/kg suggested by Fawer et al. (1999). The hydrothermal liquor production process appears to be more environmentally friendly, especially in terms of global warming, land use, and human toxicity, but with higher water consumption than the furnace liquor route.

Regarding sodium hydroxide, the membrane process is the most used (see Note S1) and it allows operation at a lower clamping voltage, lower consumption of electrical energy and steam, the possibility to change the current load on a daily basis, and minimization of environmental contamination risk. ODC represents an innovative version of the MM technology and a promising approach for reducing the electricity demand of chlor-alkali electrolysis (Fig. 8). As a result of oxygen being introduced into the cathode, hydrogen formation is suppressed and only chlorine and caustic soda are produced (Jung et al., 2014) (Fig. 8c). However, future LCA studies should focus on developing a full-scale and globally recognized database for ODC. This process has started to be used in the last decade, and it represents the future for the production of chlorine and sodium hydroxide because it requires a ten times reduced energy consumption, becoming more environmentally friendly and cost-effective (Covestro Global Corporate, 2022; Jung et al., 2014).

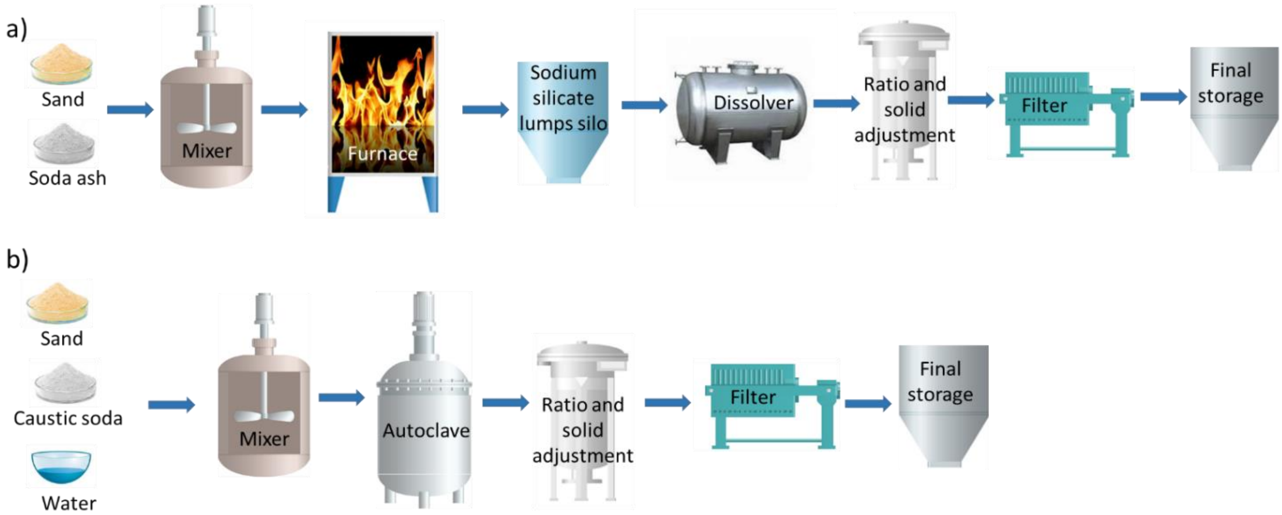

Figure 7. Sodium silicate production methods: (a) furnace and (b) hydrothermal routes.

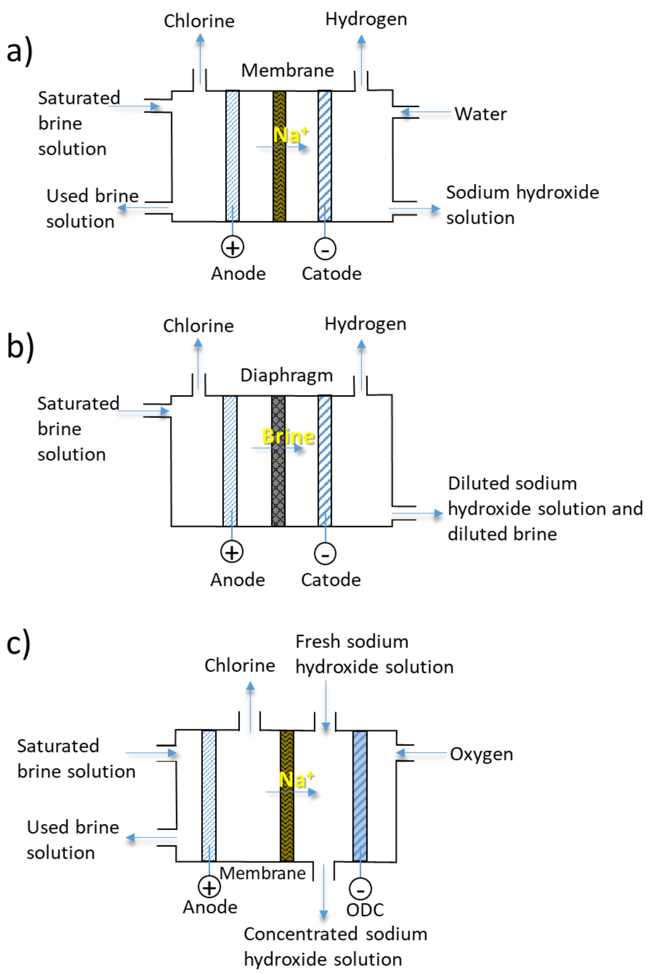

Figure 8. Sodium hydroxide production methods: (a) membrane, (b) diaphragm, and (c) ODC routes.

Conclusions

This paper aims to explore and develop alkali-activated mix designs for the S/S of MSWI FA, alternatively to OPC. With 75% of MSWI FA, the blocks fulfilled the requirements for landfill and reuse as fill materials. Overall, all the AAMs reached a higher strength than OPC.

The LCA revealed that the GGBS-based S/S treatment reduced by 60% GHG emissions compared to the OPC treatment. However, since the production of both alkali-activators was deemed the most critical unit process of the AAMs life, a focus on their production methods was developed. The hydrothermal production route for sodium silicate showed lower impacts than the furnace-based alternative, especially for land use and global warming. The membrane production method was confirmed as the best option for sodium hydroxide. The ODC-based membrane technology, revealed a substantial reduction of the impacts in every midpoint category, mainly thanks to a reduced electricity demand for chlor-alkali electrolysis. Future developments should focus on using alternative waste material as binders with suitable Si/Al molar ratios in order to minimize the use of chemicals, but also on increasing the environmental friendliness of chemicals production methods.

Acknowledgements

The authors appreciate the financial support from the Hong Kong Green Tech Fund (GTF202020153).

CRediT authorship contribution statement

Claudia Labianca: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing–original draft. **Carmen Ferrara:** Investigation, Methodology, Software, Validation, Writing–review & editing. **Yuying Zhang:** Data curation, Validation, Writing–review & editing. **Xiaohong Zhu:** Data curation, Validation, Writing–review & editing. **Giovanni De Feo:** Methodology, Supervision, Writing–review & editing. **S.C Hsu:** Methodology, Software, Writing–review & editing. **Siming You:** Methodology, Validation, Writing–review & editing. **Longbin Huang:** Conceptualisation, Validation, Writing–review & editing. **Daniel C.W. Tsang**: Resources, Methodology, Supervision, Project administration, Funding acquisition, Writing–review & editing.

References

Bajpai, R., Choudhary, K., Srivastava, A., Sangwan, K. S., Singh, M. 2020. Environmental impact assessment of fly ash and silica fume based geopolymer concrete. Journal of Cleaner Production, 254, 120147. https://doi.org/10.1016/j.jclepro.2020.120147

Bianco, I., Ap Dafydd Tomos, B., Vinai, R., 2021. Analysis of the environmental impacts of alkali-activated concrete produced with waste glass-derived silicate activator – A LCA study. Journal of Cleaner Production 316. https://doi.org/10.1016/j.jclepro.2021.128383

Billong, N., Oti, J., Kinuthia, J., 2021. Using silica fume based activator in sustainable geopolymer binder for building application. Construction and Building Materials 275, 122177. https://doi.org/10.1016/j.conbuildmat.2020.122177

BS EN 12390. 2019. Testing Hardened Concrete Compressive Strength of Test Specimens. British Standards Institution, London, UK.

Chen, L., Wang, L., Cho, D.W., Tsang, D.C.W., Tong, L., Zhou, Y., Yang, J., Hu, Q., Poon, C.S., 2019a. Sustainable stabilization/solidification of municipal solid waste incinerator fly ash by incorporation of green materials. Journal of Cleaner Production 222, 335–343. https://doi.org/10.1016/j.jclepro.2019.03.057

Chen, L., Wang, L., Cho, D.W., Tsang, D.C.W., Tong, L., Zhou, Y., Yang, J., Hu, Q., Poon, C.S., 2019b. Sustainable stabilization/solidification of municipal solid waste incinerator fly ash by incorporation of green materials. Journal of Cleaner Production 222, 335–343. https://doi.org/10.1016/j.jclepro.2019.03.057

Chen, L., Wang, L., Zhang, Y., Ruan, S., Mechtcherine, V., Tsang, D.C.W., 2022. Roles of biochar in cement-based stabilization/solidification of municipal solid waste incineration fly ash. Chemical Engineering Journal 430. https://doi.org/10.1016/j.cej.2021.132972

Cheng, H., Zhou, Y., Liu, Q., 2019. Kaolinite Nanomaterials: Preparation, Properties and Functional Applications. Nanomaterials from Clay Minerals: A New Approach to Green Functional Materials 285–334. https://doi.org/10.1016/B978-0-12-814533-3.00006-5

China's Statistic Yearbook, 2020. China's Statistic Yearbook (https://data.stats.gov.cn/easyquery.htm?cn=C01) [WWW Document].

Chindaprasirt, P., Rattanasak, U., 2018. Fire-resistant geopolymer bricks synthesized from high-calcium fly ash with outdoor heat exposure. Clean Technologies and Environmental Policy 20, 1097–1103. https://doi.org/10.1007/s10098-018-1532-4

Cleary, J., 2013. Life cycle assessments of wine and spirit packaging at the product and the municipal scale: a Toronto, Canada case study. Journal of Cleaner Production 44, 143–151. https://doi.org/10.1016/j.jclepro.2013.01.009

Colangelo, F., Farina, I., Travaglioni, M., Salzano, C., Cioffi, R., Petrillo, A., 2021. Eco-efficient industrial waste recycling for the manufacturing of fibre reinforced innovative geopolymer mortars: Integrated waste management and green product development through LCA. Journal of Cleaner Production 312, 127777. https://doi.org/10.1016/j.jclepro.2021.127777

Contessi, S., Calgaro, L., Dalconi, M.C., Bonetto, A., Bellotto, M. Pietro, Ferrari, G., Marcomini, A., Artioli, G., 2020. Stabilization of lead contaminated soil with traditional and alternative binders. Journal of Hazardous Materials 382, 120990. https://doi.org/10.1016/j.jhazmat.2019.120990

Covestro Global Corporate, 2022. Energy-saving chlorine production (Accessed on the 22/04/2022 https://www.covestro.com/en/sustainability/flagship-solutions/oxygen-depolarized-cathode?msclkid=09755175c21611ec9c0509934ab813b1) [WWW Document].

Dal Pozzo, A., Carabba, L., Bignozzi, M.C., Tugnoli, A., 2019. Life cycle assessment of a geopolymer mixture for fireproofing applications. International Journal of Life Cycle Assessment 24, 1743–1757. https://doi.org/10.1007/s11367-019-01603-z

Davidovits, J., 2009. Geopolymer, Chemistry and Applications. Lulu enterprises Inc., Morrisville, NC, USA, 574 [WWW Document]. URL https://scholar.google.com/scholar_lookup?title=Geopolymer%2C%20Chemistry%20and%20Applications&publication_year=2009&author=J.%20Davidovits (accessed 4.22.22).

De Gisi, S., Todaro, F., Mesto, E., Schingaro, E., Notarnicola, M., 2020. Recycling contaminated marine sediments as filling materials by pilot scale stabilization/solidification with lime, organoclay and activated carbon. Journal of Cleaner Production 269, 122416. https://doi.org/10.1016/j.jclepro.2020.122416

Del Valle-Zermeño, R., Formosa, J., Chimenos, J.M., Martínez, M., Fernández, A.I., 2013. Aggregate material formulated with MSWI bottom ash and APC fly ash for use as secondary building material. Waste Management 33, 621–627. https://doi.org/10.1016/j.wasman.2012.09.015

Dry Cargo International, 2022. Cargo by rail and barge – cost-efficiency combines with environmental protection [WWW Document]. URL https://www.drycargomag.com/cargo-by-rail-and-barge-—-cost-efficiency-combines-with-environmental-protection (accessed 4.8.22).

Dung, N.T., Unluer, C., 2017. Carbonated MgO concrete with improved performance: The influence of temperature and hydration agent on hydration, carbonation and strength gain. Cement and Concrete Composites 82, 152–164. https://doi.org/10.1016/j.cemconcomp.2017.06.006

Ecoinvent, 2016. Cement, Portland, {RoW}|production|APOS, U. Swiss Centre for Life Cycle Inventories.

Fan, C., Wang, B., Zhang, T., 2018. Review on cement stabilization/solidification of municipal solid waste incineration fly ash. Advances in Materials Science and Engineering 2018. https://doi.org/10.1155/2018/5120649

Fawer, M., Concannon, M., Rieber, W. 1999. LCA Case Studies LCI for the Production of Sodium Silicate Life Cycle Inventories for the Production of Sodium Silicates. https://doi.org/10.1007/BF02979498

GB/T 15581-2016. 2016. Emission standard of pollutants for caustic alkali and polyvinyl chloride industry.

GB 34330, 2017. Identification Standards for Solid Wastes-General Rules. Ministry of Environmental Protection, China.

Guo, B., Tan, Y., Wang, L., Chen, L., Wu, Z., Sasaki, K., Mechtcherine, V., Tsang, D.C., 2021. High-efficiency and low-carbon remediation of zinc contaminated sludge by magnesium oxysulfate cement. Journal of Hazardous Materials 408, 124486. https://doi.org/10.1016/j.jhazmat.2020.124486

Habert, G., D'Espinose De Lacaillerie, J.B., Roussel, N., 2011. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. journal of cleaner production 19, 1229–1238. https://doi.org/10.1016/j.jclepro.2011.03.012

Habert, G., Ouellet-Plamondon, C., 2016. Recent update on the environmental impact of geopolymers. RILEM Technical Letters 1, 17–23. https://doi.org/10.21809/rilemtechlett.2016.6
HJ 1134, 2020. Technical Specification for Pollution Control of Fly-ash from Municipal Solid Waste Incineration. Ministry of Environmental Protection, China.
HK EPD, 2022. Integrated Waste Management Facilities, HK EPD [WWW Document]. URL https://www.epd.gov.hk/epd/english/environmentinhk/waste/prob_solutions/WFdev_IWMF.html (accessed 3.23.22).
HK EPD, 2018. Tackling Imminent Waste Management Problem Integrated Waste Management Facilities Environmental Protection Department, Hong Kong SAR Government.
HK EPD, 2011. Practice Guide for Investigation and Remediation of Contaminated Land Environmental Protection Department, Hong Kong SAR Government.
Hossain, M.U., Dong, Y., Ng, S.T., 2021. Influence of supplementary cementitious materials in sustainability performance of concrete industry: A case study in Hong Kong. Case Studies in Construction Materials 15, e00659. https://doi.org/10.1016/j.cscm.2021.E00659
Hossain, M.U., Sohail, A., Ng, S.T., 2019. Developing a GHG-based methodological approach to support the sourcing of sustainable construction materials and products. Resources, Conservation and Recycling 145, 160–169. https://doi.org/10.1016/j.resconrec.2019.02.030
Hossain, M.U., Wang, L., Chen, L., Tsang, D.C.W., Ng, S.T., Poon, C.S., Mechtcherine, V., 2020. Evaluating the environmental impacts of stabilization and solidification technologies for managing hazardous wastes through life cycle assessment: A case study of Hong Kong. Environment International 145, 106139. https://doi.org/10.1016/j.envint.2020.106139
Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. International Journal of Life Cycle Assessment 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y
Huntzinger, D.N., Eatmon, T.D., 2009. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. Journal of Cleaner Production 17, 668–675. https://doi.org/10.1016/j.jclepro.2008.04.007

ISO, 2006. ISO 14040: Environmental management: life cycle assessment, principles and guidelines. International Organization for Standardization, Geneva.

Jeremiah, J.J., Abbey, S.J., Booth, C.A., 2021. Geopolymers as Alternative Sustainable Binders for Stabilisation of Clays — A Review. Geotechnics, 1(2), 439-459. https://doi.org/10.3390/geotechnics1020021

Jin, M., Zheng, Z., Sun, Y., Chen, L., Jin, Z., 2016. Resistance of metakaolin-MSWI fly ash based geopolymer to acid and alkaline environments. Journal of Non-Crystalline Solids 450, 116–122. https://doi.org/10.1016/j.jnoncrysol.2016.07.036

Juenger, M.C.G., Snellings, R., Bernal, S.A., 2019. Supplementary cementitious materials: New sources, characterization, and performance insights. Cement and Concrete Research. https://doi.org/10.1016/j.cemconres.2019.05.008

Jung, J., Postels, S., Bardow, A., 2014. Cleaner chlorine production using oxygen depolarized cathodes? A life cycle assessment. Journal of Cleaner Production 80, 46–56. https://doi.org/10.1016/j.jclepro.2014.05.086

Kanhar, A.H., Chen, S., Wang, F., 2020. Incineration Fly Ash and Its Treatment to Possible Utilization : A Review. Energies, 13(24), 6681. https://doi.org/10.3390/en13246681

Krivenko, P., 2017. Why Alkaline Activation-60 Years of the Theory and Practice of Alkali-Activated Materials. Article in Journal of Ceramic Science and Technology 323–334. https://doi.org/10.4416/jcst2017-00042

Li, Y., Min, X., Ke, Y., Liu, D., Tang, C., 2019(a). Preparation of red mud-based geopolymer materials from MSWI fly ash and red mud by mechanical activation. Waste Management 83, 202–208. https://doi.org/10.1016/j.wasman.2018.11.019

Li, N., Shi, C., Zhang, Z., 2019(b). Understanding the roles of activators towards setting and hardening control of alkali-activated slag cement. Composites Part B: Engineering 171, 34–45. https://doi.org/10.1016/j.compositesb.2019.04.024

McLellan, B.C., Williams, R.P., Lay, J., Van Riessen, A., Corder, G.D., 2011. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. Journal of Cleaner Production 19, 1080–1090. https://doi.org/10.1016/j.jclepro.2011.02.010

Passuello, A., Rodríguez, E.D., Hirt, E., Longhi, M., Bernal, S.A., Provis, J.L., Kirchheim, A.P., 2017. Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators. Journal of Cleaner Production 166, 680–689. https://doi.org/10.1016/j.jclepro.2017.08.007

Patrisia, Y., Law, D. W., Gunasekara, C., Wardhono, A. 2022. Life cycle assessment of alkali-activated concretes under marine exposure in an Australian context. Environmental Impact Assessment Review, 96, 106813. https://doi.org/10.1016/j.eiar.2022.106813

PRé Consultants, 2019. SimaPro 9.0049 version. PRé Consultants, The Netherlands.

Provis, J.L., Arbi, K., Bernal, S.A., Bondar, D., Buchwald, A., Castel, A., Chithiraputhiran, S., Cyr, M., Dehghan, A., Dombrowski-Daube, K., Dubey, A., Ducman, V., Gluth, G.J.G., Nanukuttan, S., Peterson, K., Puertas, F., van Riessen, A., Torres-Carrasco, M., Ye, G., Zuo, Y., 2019. RILEM TC 247-DTA round robin test: mix design and reproducibility of compressive strength of alkali-activated concretes. Materials and Structures/Materiaux et Constructions 52, 1–13. https://doi.org/10.1617/s11527-019-1396-z

Provis, J.L., Duxson, P., van Deventer, J.S.J., 2010. The role of particle technology in developing sustainable construction materials. Advanced Powder Technology 21, 2–7. https://doi.org/10.1016/j.apt.2009.10.006

Puligilla, S., Chen, X., Mondal, P. 2019. Does synthesized CSH seed promote nucleation in alkali activated fly ash-slag geopolymer binder?. Materials and Structures, 52(4), 1-13. https://doi.org/10.1617/s11527-019-1368-3

Qiang, T., Heejong, K., Kazuto, E., Takeshi, K., Toru, I., 2015. Size effect on lysimeter test evaluating the properties of construction and demolition waste leachate. Soils and Foundations 55, 720–736. https://doi.org/10.1016/j.sandf.2015.06.005

Rashad, A.M., 2013. Alkali-activated metakaolin: A short guide for civil Engineer – An overview. Construction and Building Materials 41, 751–765. https://doi.org/10.1016/j.conbuildmat.2012.12.030

Robayo-Salazar, R., Mejía-Arcila, J., de Gutiérrez, R. M., Martínez, E. 2018. Life cycle assessment (LCA) of an alkali-activated binary concrete based on natural volcanic pozzolan: A comparative analysis to OPC concrete. Construction and Building Materials, 176, 103-111. https://doi.org/10.1016/j.conbuildmat.2018.05.017

Salas, D.A., Ramirez, A.D., Ulloa, N., Baykara, H., Boero, A.J., 2018. Life cycle assessment of geopolymer concrete. Construction and Building Materials 190, 170–177. https://doi.org/10.1016/j.conbuildmat.2018.09.123

Shi, X., Zhang, C., Liang, Y., Luo, J., Wang, X., Feng, Y., Li, Y., Wang, Q., Abomohra, A.E.F., 2021. Life cycle assessment and impact correlation analysis of fly ash geopolymer concrete. Materials 14. https://doi.org/10.3390/MA14237375

Singh, N.B., Kumar, M., Rai, S., 2020. Geopolymer cement and concrete: Properties. Materials Today: Proceedings 29, 743–748. https://doi.org/10.1016/j.matpr.2020.04.513

Sun, K., Peng, X., Wang, S., Zeng, L., Ran, P., Ji, G., 2020. Effect of nano-SiO2 on the efflorescence of an alkali-activated metakaolin mortar. Construction and Building Materials 253, 118952. https://doi.org/10.1016/j.conbuildmat.2020.118952

Teh, S. H., Wiedmann, T., Castel, A., de Burgh, J., 2017. Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of cleaner production, 152, 312-320. https://doi.org/10.1016/j.jclepro.2017.03.122

Trabzuni, F.M.S., el Dekki, H.M., Gopalkrishnan, C.C., 2011. Process for Hydrothermal Production of Sodium Silicate Solutions and Precipitated Silicas. U.S. Patent No. 8,057,770. Washington, DC.

US EPA, 2019. Guidelines for Human Exposure Assessment (EPA/100/B-19/001)// Risk Assessment Forum. Washington, DC, U.S. Environmental Protection Agency.

Wang, L., Chen, L., Cho, D.W., Tsang, D.C.W., Yang, J., Hou, D., Baek, K., Kua, H.W., Poon, C.S., 2019. Novel synergy of Si-rich minerals and reactive MgO for stabilisation/solidification of contaminated sediment. Journal of Hazardous Materials 365, 695–706. https://doi.org/10.1016/j.jhazmat.2018.11.067

Wang, S. D., Pu, X. C., Scrivener, K. L., Pratt, P. L. (1995, published online on 2015). Alkali-activated slag cement and concrete: a review of properties and problems. Advances in cement research, 7(27), 93-102. http://dx.doi.org/10.1680/adcr.1995.7.27.93 7, 93–102.

Xue, Y., Liu, X. 2021. Detoxification, solidification and recycling of municipal solid waste incineration fly ash: A review. Chemical Engineering Journal, 420, 130349. https://doi.org/10.1016/j.cej.2021.130349

Yakubu, Y., Zhou, J., Ping, D., Shu, Z., Chen, Y., 2018. Effects of pH dynamics on solidification/stabilization of municipal solid waste incineration fly ash. Journal of Environmental Management 207, 243–248. https://doi.org/10.1016/j.jenvman.2017.11.042

Yip, C. K., Van Deventer, J. S. J. 2003. Microanalysis of calcium silicate hydrate gel formed within a geopolymeric binder. Journal of Materials Science, 38(18), 3851-3860. https://doi.org/10.1023/A:1025904905176

Zhang, Yuying, Wang, L., Chen, L., Ma, B., Zhang, Yike, Ni, W., Tsang, D.C.W., 2021. Treatment of municipal solid waste incineration fly ash: State-of-the-art technologies and future perspectives. Journal of Hazardous Materials 411, 125132. https://doi.org/10.1016/j.jhazmat.2021.125132