WITHDRAWN: Physicochemical Characteristics of Silico Manganese Slag as A Recycling Construction Material: A Systematic Review

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Abstract

Silico Manganese (SiMn) slag is a by-product of ferromanganese and silicomanganese alloy production. The large quantities of these slags have caused several challenges in disposing of them without polluting our environment. This study aims to review the physicochemical characteristics and the recycling applications of SiMn slag as construction materials. In continuation to this, a systematic review is conducted. Twenty articles were shortlisted and later assessed in terms of their physicochemical characteristics and the reutilization benefits of SiMn slag as construction materials. It is found from the literature that SiMn slag from five countries possesses similar chemical compositions such as SiO2, Al2O3, CaO, MnO, MgO, FeO+Fe2O3, and K2O+Na2O at similar quantities. Two types of slags have been identified, which are air-cooled and water-quenched SiMn slag that exhibit different physical characteristics for reutilization. Recently, studies have successfully processed SiMn slag into brick, binder/cement, paste, mortar, concrete, backfill materials, and manganese extracts. The consideration of using SiMn slag as a recycled construction material falls on cooling methods, moisture, fineness (particle size), equipment, energy, and cost. Research investigated that there are also four steps to improve the reutilization of SiMn, namely (i) incoming waste, (ii) pre-treatment, (iii) physical/chemical treatment, and (iv) products. The investigation further offers various implications and suggestions for further studies such as developing industry-scale recycling applications, environmentally friendly landfilling methods for SiMn slag, and the practicality and feasibility of SiMn-slag-based products in real projects.

1. Introduction

Silico manganese (SiMn) slag is an industrial by-product generated and collected from furnaces to produce ferro manganese (FeMn) and silico manganese alloy. The slag can be produced in various methods such as the electric submerged arc furnaces through the process of carbothermic reduction of the oxidic raw materials (Olsen and Tangstad 2004; Wallin, Ekstrøm and Tranell 2018) and the smelting processes of manganese ore through sequential steps from smelting ores, coke, fluxes and quarts in the furnaces. The process further goes through tapping, casting, refining, and crushing (Digernes et al. 2018). The SiMn alloy production is often integrated with the High Carbon FeMn alloy (HC FeMn) production because the slag from smelting HC FeMn can be reprocessed by adding into the subsequent reproduction i.e., SiMn alloy. Thus, this process is widely used in producing SiMn alloy and ensures the maximum extraction of available manganese composites from the manganese ore (El-Faramawy et al. 2004; Olsen, Tangstad and Lingstad 2007; Ringdalen et al. 2010).

In Fig. 1, the production of SiMn alloy production and SiMn slag generation is illustrated. Three tonnes of raw materials for SiMn alloy production consists of manganese ore, HC slag, quartz, dolomite, Si-sculls, and coke, which are smelted and fused under a 27 MW submerged arc furnace. The process emits carbon dioxide and dust that are discarded. The production from the furnace is a mixture of slag and metal. Only a portion of 390 kg of remelting is reprocessed in the subsequent production of SiMn alloy by adding to the raw materials. The remaining mixture of slag and metal is separated through the skimmer or cascade tapping as depicted in Fig. 2. Both the separation methods adopted density differences between the slag and metal. Further, the mixture stratifies with the heavier metal settled at the bottom layer with the slag at the top layer and then further separated similarly for the subsequent slag separation (Olsen 2007).

A few studies recycled the SiMn slag by partially replacing the coarse aggregate in the cement mix with the slag (Cahya Mata Sarawak Berhad 2018). Although the result showed a significant 50% increase in concrete strength, the preliminary study could not produce consistent quality of the concrete mix. Besides, similar types of waste can be de-scheduled as construction materials in other countries, especially after specific treatments to ensure the products can cause no harm to humans and nature. For example, China, India, Iran, Spain, and South Korea have recently conducted studies to reutilize SiMn slag as aggregates replacement in the concrete, mortar, and paste. Their results demonstrated positive outcomes in their compression and flexural strength. Furthermore, the reutilizing of SiMn slag as a useable construction material provides another option to overcome the growing depletion of river sand. This could be utilized as fine aggregates in the concrete. Besides, it can divert the SiMn slag from our landfills while providing an alternative construction material.

The remaining of this paper is organized as follows. Section 2 focuses on systematic literature review which further includes article selection process. Section 3 exclusively entails the result and discussion based on outcome of the review. Finally, conclusion is presented in Section 4.

2. Systematic Review

This study aims to conduct a systematic review in assessing the physicochemical characteristics of SiMn slag and its recycling potential as construction materials. The review process adheres to a systematic approach by following the core principles of the systematic reviews to prevent bias in the inclusions, assessment, and synthesis of studies (Schünemann and Moja 2015). Thus, this study follows similar methodologies by Chu et al. (2020) for the systematic review by initiating searching published articles and establishing selection criteria to avoid bias. Generally, it consists of setting search strategies and selection criteria and then data collection, which entails a screening process to review the articles through titles, abstracts, and data.

2.1. Search strategies and selection criteria

We selected ScienceDirect, Scopus, SpringerLink and ResearchGate as the primary database for published articles. The search and selection process took place from September 2019 to April 2020. Thus, only the published articles before April 2020 are included in this study. F0or this investigation, a few inclusion and exclusion selection criteria are established i.e. (a) only papers from 2005 to 2020 are included because most recent studies have been referring to Frías's works between 2005 and 2009 regarding the early utilization of SiMn slag as a construction material; hence, we excluded any articles before 2005, (b) the study only focuses on articles with positive outcomes of reutilization of SiMn slag; hence, we do not consider those with adverse outcomes because they do not necessarily indicate the impossibility of the reutilization of SiMn slag, and (c) and only articles written in English are considered, hence, we excluded any non-English articles without translation. Figure 3 shows the flowchart of the systematic review for collecting articles. The search process is initiated by deciding the keywords, the main keyword for this project was "silico manganese slag." However, four variations of the keyword were utilized such as *"silico manganese slag" OR "silicomanganese slag" OR "SiMn slag" OR "silico-manganese slag".*

2.2. Data collection

This process includes article inclusion and exclusion process which removes irrelevant articles. We had removed those articles with irrelevant slag types, identical results, and non-English. Figure 4 shows the number of articles collected after searching, selection, and exclusion. In the first process, we identified 265 articles from the sources. ScienceDirect showed 55 results, but only 14 are relevant to the SiMn slag, whereas other results showed other types of slag such as Mn slag or Fe slag. Scopus showed similar results to ScienceDirect. However, SpringerLink showed 143 results, including the same content as the previous sources. The result by SpringerLink remained relevant to the SiMn slag only in the first quarter of the results. At the same time, ResearchGate provided different articles in addition to the duplicated results earlier. Then, we screened out the papers using title, and abstracts for their relevance to SiMn slag, reutilization, benefits, and credibility of SiMn slag as a construction material. We found 200 irrelevant articles with irrelevant types of slag, 14 duplications of results with other sources, and 3 non-English. Lastly, only 20 articles were retrieved from the 4 sources and subjected to further appraisal.

3. Result And Discussion

Table 1 summarizes the selected 20 articles from the systematic review process. The shortlisted articles are tabulated based on their production category, authors, country, title, journal, source, and reutilization methods. We categorized them into binder/cement, brick, mortar, paste, concrete, backfilling, and raw manganese. Subsequently, we assessed each article for the physicochemical characteristics of the SiMn slag and its reutilization benefits as construction materials, including the recycling application methods, the interpretation, results of applications, knowledge gaps, and future studies. Finally, we synthesized the critical governing factors and strategies for reutilizing SiMn slag, including making arguments and references between authors during the review process.

3.1. Physicochemical characteristics of SiMn slag

SiMn slag is a by-product of SiMn alloy and FeMn alloy in carbothermal reduction of oxides ores, which are generally discarded from the main product in the electric arc furnace (Ayala and Fernández 2015). Two types of SiMn slag have been studied so far, i.e., air-cooled and water-quenched SiMn slag. The air-cooled or air-quenching method is a common industrial practice to cool down and isolate the SiMn slag from the furnace by air. This process allows the slag to solidify slowly and results in a lump formation with a partly glassy and partly crystalline nature. Besides, water-quenching is pouring molten SiMn slag from the furnace into the water to allow rapid cooling and solidification. Due to the rapid solidification, the generated slag is mostly in glassy form and brittle nature, enabling the slag to be ground more efficiently with less energy needed. Water-quenched SiMn slag also exhibited higher reactivity than the air-cooled SiMn slag (Zhang et al. 2011; Nath & Kumar 2016, 2019).

Table 1
Summary of selected articles after data collection.

Category	Authors	Country	Title	Source	Methods
Binder/Cement	Allahverdi & Ahmadnezhad (2014)	Iran	Mechanical activation of silicomanganese slag and its influence on the properties of Portland slag cement	Powder Technology	Produce Portland Slag Cement by mixing ground SiMn slag, clinker, and gypsum with slag inclusion 35wt%.
	Nath & Kumar (2016)	India	Evaluation of the suitability of ground granulated silico-manganese slag in Portland slag cement	Construction and Building Materials	Produce Portland Slag Cement by grinding 60wt% cement clinker, 10wt% SiMn slag, and 30wt% Granulated Blast Furnace Slag.
	Nath & Kumar (2017)	India	Reaction kinetics, microstructure and strength behavior of alkali activated silico-manganese (SiMn) slag – Fly ash blends	Construction and Building Materials	Blend 80wt% ground SiMn slag with 20wt% Fly ash to produce an alkali-activated binder.
	Nath & Kumar (2019)	India	Influence of Granulated Silico-Manganese Slag on Compressive Strength and Microstructure of Ambient Cured Alkali-Activated Fly Ash Binder	Waste and Biomass Valorization	
	Bhagath Singh & Subramaniam (2019)	India	Production and characterization of low-energy Portland composite cement from post-industrial waste	Journal of Cleaner Production	Produce Portland Composite Cement with 60wt% clinker, 22% fly ash, 10% SiMn slag, 2% Gypsum, 0.5% Sodium Sulphate and 0.5% Sodium Hydroxide
	Kumar et al. (2013)	Spain	Development of alkali-activated cement from mechanically activated silico-manganese (SiMn) slag	Cement & Concrete Composites	Studied mechanical activation by mills on SiMn slag. The ground SiMn slag powder is combined with 6M NaOH solution with a slag powder/solution ratio of 0.35.
	Navarro et al. (2017)	Spain	Optimization of the alkali activation conditions of ground granulated SiMn slag	Construction and Building Materials	Combining ground SiMn slag, Portland Cement and Alkaline Solution to produce a paste.
Brick	Shao et al. (2017)	China	Recycling of Si-Mn Slag in the Preparation of Unburned Water Permeable Bricks	3rd International Conference on Green Materials and Environmental Engineering (GMEE 2017)	Prepare unburned water permeable bricks using SiMn slag. Water-quenched SiMn slag (primary aggregate), Portland Cement, retail gravel, and polycarboxylate superplasticizer.
Mortar	Frías et al. (2005)	Spain	Properties of SiMn slag as a pozzolanic material in Portland cement manufacture	Mater Construcc	Replacing 5% or 15% of Portland Cement with ground SiMn slag in mortar production.
	Frias et al. (2006)	Spain	Recycling of silicomanganese slag as pozzolanic material in Portland cements: Basic and engineering properties	Cement & Concrete Composites	

Category	Authors	Country	Title	Source	Methods
	Frías & Rodríguez (2008)	Spain	Effect of incorporating ferroalloy industry wastes as complementary cementing materials on the properties of blended cement matrices	Cement & Concrete Composites	
	Zhang et al. (2011)	China	Hydration mechanism of a cementitious material prepared with SiMn slag	International Journals of Minerals, Metallurgy and Materials	Grinding 80wt% SiMn slag with 10wt% anhydrite and 10wt% lime.
	Choi et al. (2017)	South Korea	Hydrothermal reaction according to the CaO/SiO2 mole-ratio in silico-manganese slag"	J Mater Cycles Waste Manag	Grinding 17% cement and 83% SiMn slag powder for mortar preparation.
	Bhagath Singh & Subramaniam (2019)	India	Production and characterization of low-energy Portland composite cement from post-industrial waste	Journal of Cleaner Production	Produce Mortar by mixing Portland Composite Cement (10% SiMn slag) with fine aggregates, coarse aggregates, and water.
	Navarro et al. (2018)	Spain	Mechanical properties of alkali-activated ground SiMn slag mortars with different types of aggregates	Construction and Building Materials	Combining ground SiMn slag, Portland Cement and Alkaline Solution to produce mortar.
	Navarro et al. (2020)	Spain	Corrosion resistance of steel reinforcements embedded in alkali activated ground granulated SiMn slag mortars	Construction and Building Materials	
Paste	Frías, Rojas & Rodríguez (2009)	Spain	The influence of SiMn slag on chemical resistance of blended cement pastes	Construction and Building Materials	Replacing 5% or 15% of Portland Cement with ground SiMn slag for paste preparation.
Concrete	Ganesh et al. (2018)	India	Influence of Silico Manganese Slag on Mechanical and Durability Properties of Concrete	International Journal of Civil Engineering and Technology	Replace 50% of coarse aggregates (crushed granite) with raw SiMn slag and then mix with Portland cement, river sand, crushed granite, and water.
Backfilling Materials	Rohit Kumar & Lokesh (2013)	Spain	Geotechnical Characterization of Silico Manganese Slag for Civil Engineering	4th Indian Young Geotechnical Engineers Conference	Raw SiMn slag can be used as backfilling materials, lightweight fill materials for retaining walls, and preparation for soil beds.
Raw Manganese Material	Kim et al. (2011)	South Korea	Upgrading of Manganese from Waste Silicomanganese Slag by a Mechanical Separation Process	Materials Transactions	Grind SiMn slag into powder and feed into a Magnetic Separation Apparatus to collect raw Manganese.

Category	Authors	Country	Title	Source	Methods
	Ayala & Fernández (2015)	Spain	Recovery of manganese from silicomanganese slag by means of a hydrometallurgical process	Hydrometallurgy	Grind SiMn slag into powder and apply hydrometallurgical process: Dissolution of Manganese, Purification of leach Solutions, and Electrowinning.

The chemical compositions of SiMn slag were studied by 19 authors in five different countries through various processes. However, one of the most common identification methods was found as grinding the SiMn slag into powder size and characterizing it *via* a powder X-ray diffractometer (XRD). Zhang et al. (2011) adopted the water-quenched approach and experimented with the hydration mechanism on SiMn slag from Guangxi province in China. The slag had a grain size of 3–5 mm, a density of 2.8 g cm^{-3}, and exhibited a light green color and glassy appearance. The chemical analysis of the slag indicates a significant amount of SiO_2, CaO, Al_2O_3, MgO, and MnO (wt%). Shao et al. (2017) also collected water-quenched SiMn slag from Wuhan, China, which was porous and grey-green. The slag was dried at 110°C for 24 hours in an oven and analyzed by ICP-AES. Similar content and quantity were also found in the slag, such as SiO_2, CaO, Al_2O_3, and other oxides.

Nath & Kumar (2016) and Nath & Kumar (2019) retrieved and ground the water-quenched SiMn slag from Chhattisgarh, India. The sample was characterized by ICP-OES (Vista MPX, Varian), X-ray fluorescence (XRF, SRS 3400, Make: Bruker, US), and conventional wet chemical method. The results also demonstrated similar content and quantity of SiO_2, CaO, Al_2O_3, MgO, and MnO, similar to studies in China. Nath & Kumar (2017) further investigated the utilization of SiMn slag to develop alkali-activated cement. The SiMn slag in this study was air-cooled and retrieved from Durgapur, India, different from the water-quenched sample from Chhattisgarh. The chemical compositions followed their previous studies, and the results showed similar content but different quantities, especially in CaO and Al_2O_3. On the other hand, Ganesh et al. (2018) examined the usage of SiMn slag as coarse aggregate; however, they did not report the origin and identification methods of the chemical compositions. The results, otherwise, showed similar content but with different quantities of SiO_2, CaO, Al_2O_3, MgO, FeO, and MnO. Furthermore, Bhagath Singh & Subramaniam (2019) collected SiMn slag from Kothagudem, India, and characterized it by X-ray Fluorescence Spectrometer (XRF) with X-flash silicon was used to identify the chemical compositions. The result indicated similar compositions but with a different quantity of oxides compared to the abovestated studies. Allahverdi & Ahmadnezhad (2014) investigated the utilization of SiMn slag in mechanical activation in Portland Slag Cement. The slag was obtained from Hormozgan province in Iran and followed with tests to determine its properties by wet chemical analysis, powder XDR Diffractometry, FTIR Spectroscopy, and Thermogravimetry. The slag exhibited similar content and quantity as in studies by Nath & Kumar (2016) and Nath & Kumar (2019).

Frías et al. (2005) explored the behavior of the SiMn slag as a pozzolanic material in Portland Cement. The SiMn slag was collected from Guarnizo, Cantabria, Spain, and the chemical compositions were analyzed by ICP and powder XRD. The results did not show significant differences in content and quantity from the above studies. Moreover, in the other studies by Frías et al. (2005), Frias et al. (2006), Frías & Rodríguez (2008), Frías, Rojas & Rodríguez (2009) and Kumar et al. (2013), the same slag and identification methods by powder XRD were carried out, and the content and quantity were found identical to those in the study by Frías et al. (2005) and their subsequent researches. On the other hand, Ayala & Fernández (2015) proposed a hydrometallurgical process to recover Mn from Spanish SiMn slag using a leach solution. The process involved identifying oxides in SiMn slag *via* atomic absorption spectroscopy following acid digestion and gravimetric technique. The content and quantity were similar to other studies with no significant differences. Another research team, Navarro et al. (2017), studied the feasibility of utilizing SiMn slag as a raw material in an alkali-activated binder. The slag shared the same source and characterization methods by powder XRD as in Frías et al. (2005). The findings showed that the slag consisted of fair similarity with notable differences despite having the exact origin. It exhibited a lower quantity of SiO_2 and Al_2O_3 but higher in CaO and MnO. It is found that the chemical analysis was also referred to and indicated the same results in Navarro's subsequent studies (Navarro et al. 2018, 2020).

Choi et al. (2017) studied water-quenched SiMn slag and its hydrothermal reaction. They collected the slag from D. Co. Ltd. in South Korea. SiO_2, Al_2O_3, MnO, CaO, and MgO were found in the chemical analysis; however, the quantity differed slightly from other studies. In addition, Kim et al. (2011) explored the feasibility of Mn recovery from SiMn slag by a mechanical separation process. The process involved in X-ray to determine compositions in the slag. However, the results differed significantly from other studies as only some oxides, metals, and other elements were shown instead of oxides. SiO_2, Al_2O_3, MnO, and CaO were the oxides identified, whereas others were pure elements such as Zn, Mn, Cr, Pb, P, Na, K, and Fe.

Table 2 summarizes the chemical compositions identified from the shortlisted articles through various characterization tests. The SiMn slag was reportedly retrieved from FeMn alloy, SiMn alloy, and other alloy industries. The commonly found compositions are oxides such as SiO_2, CaO, MnO, Al_2O_3, MgO, FeO and Fe_2O_3, K_2O and Na_2O, TiO_2, SO_3, and other compositions which are either unidentified or unreported. All the studies supported that SiMn slag exhibited SiO_2 content, approximately more than a quarter of the total wt%, and CaO, MnO and Al_2O_3 represented another significant portion of the compositions. The Loss on Ignition (LOI) was recorded to indicate the mass loss after heating. Figure 5 shows the average chemical compositions of SiMn slag based on Table 2, excluding the data from Kim et al. (2011) due to different oxide content being measured compared to other studies. In short, the SiMn slag comprises 36.98 wt% SiO_2, 22.82 wt% CaO, 10.71 wt% MnO, 15.81 wt% Al_2O_3, 4.75 wt% MgO, 1.25 wt% FeO + Fe_2O_3, 3.42 wt% K_2O + Na_2O, and 1.90 wt% of other compositions. Despite the different oxide content being measured in Kim et al. (2011), a similar quantity regarding SiO_2, CaO, Al_2O_3, and MgO in the study.

Table 2
Chemical Compositions of SiMn slag (wt%) in China, India, Iran, Spain and South Korea.

Country	Reference	Source	SiO_2	CaO	MnO	Al_2O_3	MgO	FeO + Fe_2O_3	K_2O + Na_2O	Others/ N.R	LOI
China	Zhang et al. (2011)	Heshan, Guangxi	29.02	17.14	4.65	25.01	5.59	1.46	1.55	2.34	0.2
	Shao et al. (2017)	Lab: Wuhan, China	39.25	14.54	12.25	24.89	5.29	0.9	2.63	0.27	N.R
India	Nath & Kumar (2016); Nath & Kumar (2019)	Chhattisgarh	40.33	26.17	10.06	14.55	5.74	0.75	0	0.69	N.R
	Nath & Kumar (2017)	Durgapur	36.4	17.74	11.23	25.94	4.27	1.2	0.58	0.12	2.2
	Ganesh et al. (2018)	Vizianagaram	42.11	24.68	12.45	10.36	6.12	0.84	0	0.00	N.R
	Bhagath Singh & Subramaniam (2019)	Kothagudem	28.42	22.34	3.5	9.22	3.75	2.33	26.36	3.75	0.31
Iran	Allahverdi & Ahmadnezhad (2014)	Hormozgan	38.17	29.3	10.29	14.78	2.77	1.79	1.18	0.12	1.12
Spain	Frías et al. (2005, 2006); Frías & Rodríguez (2008); Frías, Rojas & Rodríguez (2009); Kumar et al. (2013)	Boo-de-Guarnizo (Cantabria)	42.6	25.2	9.9	12.2	4.2	1	2.56	0.78	N.R
	Ayala & Fernández (2015)	Lab: Oviedo, Spain	41.64	24.78	10.84	11	5.3	2.28	1.33	0.44	N.R
	Navarro et al. (2017, 2018, 2020)	Boo-de-Guarnizo (Cantabria)	36.53	29.1	12.23	9.86	4.69	0.92	1.42	5.95	-1.25
South Korea	Choi et al. (2017)	D. Co. Ltd.	32.3	20	20.4	16.1	4.55	0.3	0	6.40	N.R
	Reference	**Source**	**SiO_2**	**CaO**	**Mn**	**Al_2O_3**	**MgO**	**Fe**	**K + Na**	**Pb**	**Others**
	Kim et al. (2011)	Dongbu Metal Company	38.61	15.67	14.1	14.76	4.83	0.77	2.87	0.11	0.01
[*LOI = Loss on Ignition; N.R = Not Reported]											

3.2. Reutilization of SiMn slag

Approximately 1.2 to 1.4 tonnes of SiMn slag are generated annually for each ton of SiMn alloy production. However, the current conventional disposal method of SiMn slag is mainly by landfill, which is not environmentally friendly (Ayala and Fernández, 2015). Recent studies have diverted the focus from steel slag onto SiMn slag as steel slag has received sufficient attention in recycling practices but not SiMn slag. China, India, Iran, and South Korea have been presently conducting experiments to recycle

SiMn slag as construction materials in the 2010s. However, Spain initiated earlier than the rest in 2005 and made adequate progress. The subsequent sections present various possible SiMn slag recycling practices for construction materials.

3.2.1. Binder/Cement

Several studies indicate the viability of incorporating ground SiMn slag in Portland cement to produce alkali-activated binder or Portland composite/slag cement. Allahverdi & Ahmadnezhad (2014) investigated the mechanical activations of SiMn slag along with its influence on Portland Slag Cement production by utilizing granulated air-cooled SiMn slag as supplementary cementing material. SiMn slag, clinker, and gypsum were mixed and ground in a ball mill in four different Blaine-specific surface areas. Water was then added to the mixtures to mold them into 40 x 40 x 160 mm prism and cured accordingly. The experimental results proved the effectiveness of mechanical activation of SiMn slag inclusion up to 35 wt% (combined with 65 wt% of clinker and gypsum) with no significant variation in setting times, chemical requirements, and volume instability. Hence, it is estimated that 1 to 35 wt% SiMn may be added to Portland Slag Cement to produce 25 to 40 MPa of compressive strength after 28 d curing.

In addition, Nath & Kumar (2016) evaluated the incorporation of SiMn slag into Portland Slag cement. The obtained SiMn slag underwent water-quenching, rapid solidification, and granulation, which resulted in a mostly glassy nature. The SiMn slag and blast furnace slag were ground in a ball mill to reach a grain size smaller than 45 μm. Five different batches with different proportions of SiMn slag, blast furnace slag, and Portland Cement were prepared to make Portland Slag Cement which was later mixed with water and sand to create sample mortars. The sample mortars were subsequently molded in 70 x 70 x 70 mm with sand/cement ratio 3:1 and subject to 7–28 days of curing. The sample mortar with Portland Slag Cement, i.e., 60 wt% cement clinker, 10 wt% SiMn slags, and 30 wt% Granulated Blast Furnace Slag, sand, and water showed the optimal result of compressive strength with greater than 42 MPa on 28th day of curing age. Hence, the results suggested SiMn slag can be a potential raw material to replace granulated Blast Furnace Slag in the Portland Slag Cement production.

Nath & Kumar (2017) further investigated the SiMn slag reutilization for alkali-activated cement development. The SiMn slag in this study was air-cooled in lump form and later was crushed, and ball milled to reach a powder size of less than 30 μm. It is subsequently blended with fly ash to create a powder blend and then mixed with alkali solution with the powder blend/alkali solution ratio of 2:1. Five batches were prepared from the powder blend and alkali solution at different SiMn slag and fly ash proportions, while the reference batch was 100% fly ash as a binder. The batch samples were 50 x 50 x 50 mm cubes for the compressive test. The results indicated that the optimal compressive strength achieved 25 MPa when the powder blend was at 80% SiMn slag and 20% fly ash after 28 d curing. In contrast, the reference batch exhibited approximately 2 MPa only. Hence, the fly ash alone revealed limitations as in alkali-activated cement. However, fly ash with SiMn slag can eliminate the limitation when blended. Thus, the study suggested that the blend can be a potential material source for an alkali cement binder cured at ambient temperature.

A recent study on the influence of SiMn slag on compressive strength and microstructure of alkali-activated fly ash binder was conducted by Nath & Kumar (2019). Instead of using air-cooled SiMn slag, this work followed a similar process as Nath & Kumar (2017) but with water-quenched SiMn slag. The SiMn slag was milled in a ball mill for 2 h to get a powder size of less than 25 μm. Like the previous work, five batches of binder proportions were prepared by replacing 10%, 30%, 50%, 60%, and 80% of fly ash with SiMn slag. The reference batch had 100% fly ash as a binder. Each batch was mixed with 27 wt% of 6 M NaOH and cured for 7 and 28 days. The results showed that the batch with 20 wt% fly ash and 80 wt% SiMn slags as binder exhibited the highest compressive strength (35 MPa) at 28 days of curing. The inclusion of SiMn slag increased the strength as curing time increased due to the mix's enhanced reactivity and Ca-rich gel formation. Hence, it is feasible to utilize a mixture of fly ash and SiMn slag for alkaline cement synthesis. Further studies were suggested on the durability and leaching of the developed binder. On the other hand, Bhagath Singh & Subramaniam (2019) developed methods to utilize SiMn slag to manufacture Portland Composite Cement (PCC). The production components were 65% clinker, 22% fly ash, 10% SiMn slag, 2% gypsum, 0.5% sodium sulfate, and 0.5% sodium hydroxide and ground together to produce PCC.

Mechanical activation by mills has been found to correlate with the reactivity of the SiMn slag. Thus, Kumar et al. (2013) explored the mechanical activation of the reactivity of SiMn slag using three types of mills, i.e., Ball Mill (BM), Vibration Mill (VM), and Attrition Mill (AM). The SiMn slag was retrieved from Spain, crushed by Lab-scale Jaw Crusher, and later subjected to milling by different mills under different conditions. The slag was combined with 6 M NaOH alkaline activator solutions with a slag powder/solution ratio of 0.35. The sample cube size was 7 x 7 x 7 cm by Vibro-casting of paste and cured for 7 and 28 days. As a result, the mechanical activation elevated the slag's reactivity depending on the mill and affected structural reorganizations of the slag. These factors, combined with particle size, alter the alkaline activation reaction. Hence, the results may suggest the viability of incorporating SiMn slag in alkali-activated cement binder.

Navarro et al. (2017) studied the feasibility of utilizing SiMn slag as a raw material in an alkali-activated binder. The SiMn slag was collected from Spain and ground in a dry condition in a lab ball mill for 25 min to achieve a fineness of 5512 $cm^2\ g^{-1}$. The slag used is ground granulated SiMn slag with a basicity index of 0.8 and hydraulicity index of 0.85. The elemental compositions of the slag were similar to that of Portland Cement. The paste was prepared with 1800 g of SiMn slag and alkaline solution and prepared in a mixer control Automix for 3 min. The paste was cast in 4 x 4 x 4 cm cubes for the compressive strength test. The optimal compressive strength value achieved 46 MPa at 90 days with SiO_2/Na_2O ratio is 1, alkaline activator solution/slag mass ratio is lower than 0.375, $\%Na_2O$ is 4.5.

3.2.2. Brick

The feasibility and methods to prepare unburned water permeable bricks using SiMn slag were studied and proposed by Shao et al. (2017). The permeable bricks were prepared using water-quenched SiMn slag (as the primary aggregate), Portland Cement (as adhesive), 2 to 6 mm retail gravel, and polycarboxylate superplasticizer. Following Chinese brick standards JC/T 945–2005 and GB/T 25993 – 2010, the bricks were weighed, mixed in a blender, molded at a 5 MPa in 200 x 100 x 50 mm cubes, and cured for 28 days. The water/Cement ratio was 0.34 with 25 wt% cement content and 10 wt% SiMn slag content. The brick performance results showed that a 5 mm surface layer exhibited $1.08\text{x}10^{-2}$ $cm\ s^{-1}$ permeability and 33.15 MPa compressive strength, which complies with the national standard ($1\text{x}10^{-2}$ $cm\ s^{-1}$ and 30 MPa).

3.2.3. Mortars

Several studies have explored using SiMn slag in a mortar. Various types of mortar products such as alkali-activated mortar, Portland cement mortar, Portland slag mortar, Portland composite mortar, and other SiMn slag incorporated mortar are feasible in construction. Many methods were developed to test the feasibility of the slag, and the results shed light on the positivity of reusing the SiMn slag in mortar production.

Frías et al. (2005) initiated the early reutilization of SiMn slag by exploring the pozzolanic behavior of the SiMn slag in Portland Cement. The SiMn slag was collected from Guarnizo, Cantabria, Spain, and subsequently was crushed and ground to a specific Blaine fineness of 4,500 $cm^2\ g^{-1}$. Two mortar samples were prepared by having SiMn slag replacing Portland Cement with 5% and 15%. The samples were cured for 28 and 90 days and then tested. Results showed that the slag was moderately reactive with a lime solution and featured pozzolanic activities. The mortar samples exhibited mechanical strength at 90 days of curing, which met the standard of mechanical requirements for commercial cement at 42.5 to 62.5 MPa. Cement mixed with SiMn slag also adhered to the chemical requirements. As a result, it is up to 5% by weight of cement can be used to replace cement.

Moreover, Frias et al. (2006) pursued their research into SiMn slag blended cement to obtain more details. This study followed the same procedure as Frias et al. (2006). The SiMn slag was ground to 456.9 $m^2\ kg^{-1}$, and 5% and 15% of SiMn slag replacement were applied. The sand/binder ratio was kept at 3:1 and the water/binder ratio at 0.5. The samples were prepared in 4 x 4 x 16 cm prism shape and cured. The results endorsed pozzolanic activity and showed no change in cement and volume instability setting times. The mechanical strength significantly increased between 7 and 90 days, with the values almost identical to the control mortars. On the 90th day, the compressive strength of the controlled sample, 5% SiMn slag, and 15% SiMn slag were 60, 60, and 58 MPa, respectively, while the flexural strength was roughly 10, 10, and 9.5 MPa, respectively. Hence, it was feasible to suggest the viability of SiMn slag usage as pozzolanic material in blended cement.

According to the previous research, Frías & Rodríguez (2008) investigated and evaluated the characteristics of SiMn slag and Mn oxides, reutilizing these two by-products from ferroalloys productions as complementary cementing materials. Identical methods and procedures were carried out on SiMn slag and Mn oxides to partially replace Portland cement. The results of SiMn slag inclusion up to 5% and 15% remained consistent with the studies by Frias et al. (2006) and Frias et al. (2008). However, the mechanical strengths of MnO inclusion resulted in slightly lower values than those of SiMn inclusion. MnO inclusion also experienced a strength loss after curing for 90 days. It was concluded that the two by-products were applicable in Portland cement production and complied with chemical, physical, and mechanical requirements.

The hydration mechanism on water-quenched SiMn slag was investigated in mortar by Zhang et al. (2011). The slag had a light green color with a glassy appearance and a density of 2.8 g cm^{-3}. The experiment was initiated with SiMn slag and anhydrite being dried in a ball mill at 378 K. The slag was ground to a surface area of 500 m^2 kg^{-1}, and lime was added to anhydrite and ground to 400 m^2 kg^{-1}. The preparation of mortar bar samples consisted of 80 wt% SiMn slag powder, 10 wt% anhydrite, and 10 wt% lime with a water/cement ratio of 0.45. The samples were subsequently cured for 7 and 28 days. The results on the 7th day showed that mortar samples exhibited slightly lower flexural and compressive strength than the reference Ordinary Portland Cement (OPC) bar. However, the results on the 28th day showed an optimum result as the mortar bar's flexural strength reached 8.81 MPa, whereas OPC at around 6.5 MPa. The compressive strength of the mortar bar was at 51.48 MPa, which is higher than OPC's, whose value was approximately 42.5 MPa. This research suggested further studies on improving physical properties by optimizing particle size gradation and additives adjustment.

A new technique to utilize SiMn slag for pozzolanic reaction under room temperature as mortar bars was developed by Choi et al. (2017). The SiMn slag was water-quenched, then pulverized in a ball mill to achieve a fineness of over 6000 cm^2 g^{-1}. It is subsequently reheated at 900°C and let cool slowly to allow mineral crystal formation. SiMn slag powder was used to replace OPC at different proportions (0, 5, 10, or 50% of OPC) in the preparation of mortar for the compressive test. The water-to-binder ratio was kept at 0.5, while the binder-to-sand ratio was 1:3. An optimal result was achieved at 34 MPa of compressive strength when the mortar was prepared with 17% cement and 83% SiMn slag powder with a CaO/SiO_2 mole ratio of 1.0. It was confirmed that water-quenched SiMn slag through hydrothermal synthesis reaction could be served as a silica source.

Another type of SiMn slag incorporated mortar was studied by Bhagath Singh & Subramaniam (2019) by mixing Portland Composite Cement (10% SiMn slag) with fine and coarse aggregates with a water/cement ratio of 0.43. The mortar was molded in standard 150 mm cubes and cured to test the compressive strength. The results showed exponential growth of compressive strength and peaked at a value of 40 MPa on the 90th day of curing. Compared to the Ordinary Portland Cement (OPC) sample, the PCC performed better than OPC, whose compressive strength was roughly 34 MPa. Further studies suggest enhancing reaction mechanism and strength development to utilize the PCC as conventional cement.

On the other hand, Navarro et al. (2018) continued exploring the mechanical performance and stability of mortars developed by incorporating SiMn slag in the binder. According to the previous research by Navarro et al. (2018), two types of activators were used, i.e., NaOH and Waterglass solutions. Three types of aggregate were used, i.e., silica sand, limestone sand, and recycled sand from recycled concrete. The procedure was carried out following Navarro et al. (2017). The results showed the optimum mechanical performance of mortar was 68 MPa when waterglass was used as an activator, silica sand as aggregate, $\%Na_2O$ of 4.5-5% at 90 days, aggregate/slag ratio of 2:1. Good performance was also achieved by using limestone. Indications were made in further studies on the necessity of using shrinkage-reducing admixture for these types of binders. Last but not least, Navarro et al. (2020) further explored the corrosion resistance of the steel reinforcement, which was set in alkali-activated mortars using ground granulated SiMn slag. The procedure for testing mechanical performance was identical to the previous work by Navarro et al. (2018). The mortars were reinforced by steel bars and experimented with in two aggressive environments, i.e., carbonation and chloride ingress. The results showed that Waterglass provided better resistance against carbonation, whereas NaOH resistance was lower than Waterglass. Steel embedded mortars with Waterglass showed higher chloride migration coefficients. On the other hand, steel embedded mortars with NaOH provide lower corrosion rate levels.

3.2.4. Paste

In addition to the previous studies by Frías et al. (2005), Frias et al. (2006) and Frías & Rodríguez (2008), the team further explored the influence of SiMn slag on the resistance against different aggressive solutions (Frías, Rojas & Rodríguez 2009). Three paste samples were investigated, and they were the reference paste (Portland cement) and blended pastes with 5% and 15% SiMn slag inclusion. However, each paste sample was mixed with 4 solutions, i.e., 0.5 M sodium sulfate, 0.5 M sodium chloride, artificial seawater, and reference water. Specimens were molded in 1 x 1 x 6 cm and cured. Consequaently, the blended cement pastes with 5% and 15% SiMn slag inclusion after being cured for 56 days showed good resistance in some aggressive solutions. There was no weight loss but a good resistance index compared to the reference matrix. Thus, the study directed a further implication on utilizing the SiMn slag in bridge or structures near the sea.

3.2.5. Concrete

The mechanical and durability properties of concrete partially incorporated with SiMn slag as coarse aggregate were examined by Ganesh et al. (2018). The project aimed to develop an Ordinary Portland Cement at grade M30. The ingredients used were Portland Cement, river sand, crushed granite, and water at a water/cement ratio of 0.45. Four mortar samples were prepared with SiMn slag, which was partially used to replace crushed granite by 25%, 50%, 75%, and 100%. The samples were then mixed, cast in a lab, and cured for 7 and 28 days. As a result, only 50% replacement of SiMn slag with crushed granite demonstrated optimal compressive strength value at 38.52 MPa at 28 days, similar to a control concrete mix (38.80 MPa). The 50% replacement showed higher resistance to acid and alkalinity. It was also tested in a minor concrete structure. Suggestions were made for further studies on microstructural analysis for a clearer understanding.

3.2.6. Backfill material

The geotechnical properties of SiMn slag for reutilizing as a replacement for sand have been explored by Rohit Kumar & Lokesh (2013). The SiMn slag was collected from Visakhapatnam, India; however, no chemical compositions were identified. The slag was then tested by I.S Heavy compaction tests with 1000 cc mold to remove moisture and achieve maximum dry density. The sieve analysis was carried out on the slag to identify the effects of compaction on grain size. The results showed that the slag had fair permeability (2 x 10^{-3} cm s^{-1}), which can be utilized as lightweight fill materials for retaining walls. The slag's density was 1.12 g cc^{-1}, while the sand's density was 1.8 g cc^{-1}; thus, the slag may be considered an alternative to conventional fine aggregate for lightweight concrete production. Moreover, it also satisfied the conditions in preparation for reinforced earth retaining walls and soil beds due to the slag's friction characteristics.

3.2.7. Raw manganese material

Two methods for Mn recovery were proposed and accessed to recover raw Mn from the SiMn slag for SiMn production and other purposes in construction. The first method was through a mechanical separation process by Kim et al. (2011). The slag was collected from Dongbu Metal Company in Korea and was first ground by a jaw, hammer, and pulverizer to reach a grain size of 500 μm. The slag powder was then sieved in four sizes + 0.280 mm, + 0.200 mm, + 150 mm, and + 75 mm. The dry magnetic separation (cross-belt types) was conducted at a magnetic field ranging from 5,000 to 10,000 tesla for each particle size. The slag powder was then fed into the magnetic field, where the magnetic particles were gripped and collected, and the non-magnetic ones were blown off. As a result, 20 mass% Mn from SiMn slag was collected when the magnetic field was around 6,000 Tesla, and the slag size ranged from − 500 μm to + 75 μm.

As much as 33% of the residing Mn can be recovered. The actual amount of Mn recovered depends on the Mn content in the slag. This process also aimed to reduce the slag volume in landfills, which generated environmental concerns. The second method was through the hydrometallurgical process by Ayala & Fernández (2015). The slag was collected, crushed, and underwent several steps, i.e., dissolution of Mn, purification of the leach solutions, and electrowinning. The SiMn slag was treated with sulfuric acid (10% by mass) in a furnace at 200°C for 30 min with 10% excessive acid to dissolve Mn. The sample was then leached with a 15 w/v% lime slurry with 1 w/v% KOH to achieve a pH of 6. Consequently, the process can recover 94% of Mn in the residue with a purity of 99.99%.

3.3. Critical governing factors of SiMn slag reutilization

3.3.1. Cooling methods

Cooling methods play an essential role in determining the types of SiMn slag for reutilization because different types of slag require different pre-treatment processes. Two cooling methods have been identified, i.e., air-cooling and water-quenching, producing two distinctive SiMn slag types, i.e., air-cooled SiMn slag and water-quenched SiMn slag. Air-cool SiMn slag has a lumpy formation with a partly glassy and crystalline nature which is a factor that requires more energy and power to grind the slag to a specific fineness for different production. However, the water-quenched SiMn slag is mostly in glassy form and brittle nature, which necessitates less energy for the grinding process but demands additional process reheating for moisture removal (Zhang et al. 2011; Nath & Kumar 2016, 2019).

3.3.2. Moisture

Water-quenched SiMn slag exhibits moisture due to the water-quenching process. As a result, it must be ground and dried to remove moisture before being blended and mixed with other cementitious materials to produce cement or binder. If moisture remains in the slag after the blending process, the moisture can initiate an early reaction with cementitious materials, reducing the quality and strength of the final product.

3.3.3. Fineness

Fineness is another factor that influences and strengthens the SiMn slag's hydraulic properties and is achieved through mechanical activation such as ball milling (Nath and Kumar, 2017). Hence, fineness is one of the requirements for reutilization processes as a construction material. Raw SiMn slag is typically obtained in lump form. It can be reused as backfill materials in retaining walls due to its high frictional characteristics (Rohit Kumar and Lokesh, 2013) and a replacement for coarse aggregates in concrete (Ganesh et al., 2018). However, for binder, cement, mortar, and paste production, SiMn slag must be pulverized in a ball mill or crusher into specific fineness ranging from 2900 to 5512 $cm^2 g^{-1}$ or from 30 to 45 μm. For raw manganese extraction, the required specific fineness must be less than 500 μm for the magnetic separator process (Kim et al., 2011) and 300 μm for hydrometallurgical processes (Ayala and Fernández, 2015).

3.3.4. Equipment

Ovens and ball mills are presently still at laboratory size and specifications. Hence, they cannot meet the demand for mass SiMn slag reutilization unless upgraded to industrial specifications to ensure the possibility of future mass recycling of SiMn slag.

3.3.5. Energy

Another factor to consider is the energy consumed by the equipment such as the oven, ball mill, crusher, and magnetic separation apparatus. Mass recycling of SiMn slag entails more extensive equipment and mass-energy consumption. For instance, the oven and ball mill processing may take up to 24 and 2 hours, respectively (Shao et al. 2017; Nath & Kumar 2017, 2019).

3.3.6. Cost

Cost determines the beneficial gain from the final product from the reutilization of SiMn slag. Water-quenched SiMn slag is less economical than the air-cooled SiMn slag because the water-quenching process requires additional costs for the water treatment plant and labor (Allahverdi and Ahmadnezhad, 2014). Moreover, extra expenditure is required to install equipment and for energy consumption.

3.4. Strategies to improve SiMn slag reutilization

Figure 6 shows a conceptual process chart for improving SiMn slag reutilization. The conceptual process starts with the types of incoming waste and then decides how to identify and separate the SiMn slag type. It is followed by "Pre-treatment, " an essential step to enable physical alteration of the slag to fit the production purposes. Lastly, the "Physical/chemical treatment" entails various methods to convert the slag into "Products."

3.4.1. Incoming waste

Two types of SiMn slag have been identified, which are air-cooled and water-quenched SiMn slag. Air-cooled SiMn slag exhibits a partly glassy and crystalline nature which is more rigid than water-quenched SiMn slag, which possesses a mostly crystalline nature (Zhang et al. 2011; Nath & Kumar 2016, 2019). Air-cooled SiMn slag is more suitable for backfilling material and requires no pre-treatment before practical use. Either type of slag can be repurposed for an alkali-activated binder with fly ash (Nath and Kumar, 2017, 2019).

3.4.2. Pre-treatment

Three types of equipment are suggested for the Pre-treatment process, all of which alter the slag's physical characteristics, such as particle size/fineness and moisture. A ball mill is an essential piece of equipment that uses iron or steel balls to grind ores or materials into powder (ZOOMJO, 2020). The SiMn slag should be ground in a ball mill before blending with specific proportions of cementitious materials, such as clinker, gypsum, or Portland cement, to produce SiMn-slag-based cement. Another piece of equipment is the crusher machine, which utilizes mechanical force to reduce the material size into gravel size. For example, a jaw crusher uses compression to crush the slag with a moveable and fixed jaw mechanism (Telsmith, 2020). The SiMn slag crushed by jaw crusher can be similar to gravel size suitable for concrete production. The third type of equipment is the oven. A laboratory oven is used to heat and dry the water-quenched SiMn slag to remove the moisture.

3.4.3. Physical/chemical treatment

Four treatment methods are suggested to create the final product from SiMn slag. Here, we briefly describe them: (a) combining slag with other materials or elements using a mixer (the slag functions as a binder, cement, or coarse aggregate according to the purpose of production), (b) separating Mn by a magnetic separator apparatus, (c) dissolution, leaching, purification, and electrowinning (by electrode) to extract Mn, and lastly (d) molding the SiMn slag along with other materials for brick production.

3.4.4. Process and products

Eight different products can be produced from the reutilization of SiMn slag (Fig. 6). Raw air-cooled SiMn slag can be used as backfill materials to construct earth retaining walls and prepare reinforced soil beds (Rohit Kumar and Lokesh, 2013). For various cement production, air-cooled SiMn slag can be ground in a ball mill to reach a certain fineness and mixed with cementitious materials. Morever, ground SiMn slag with a fineness of < 456.9 $m^2\ kg^{-1}$ can replace 5% or 15% of Portland cement (Frías et al., 2005; Frias et al., 2006; Frías and Rodríguez, 2008; Frías, Rojas and Rodríguez, 2009), and the same slag along with a combination of clinker and gypsum in a proportion of 35% and 65% respectively can be ground in a ball mill to produce Portland Slag cement with fineness ranging from 2900 to 4100 $cm^2\ g^{-1}$ (Allahverdi and Ahmadnezhad, 2014).

Another type of cement, Portland Composite cement, can also be produced by grinding 10% SiMn slag, 65% clinker, 22% fly ash, 2% gypsum, 0.5% sodium sulfate, and 0.5% sodium hydroxide (Bhagath Singh and Subramaniam, 2019). Moreover, the SiMn-slag-based cement mentioned above can be utilized to produce paste by adding water. The SiMn-slag-based cement can also be further repurposed for mortar productions by adding water and fine aggregate, commonly river sand. In short, two types of concrete can be developed from SiMn slag. The first type is ball-mill-processed SiMn slag, which is a partial replacement of Portland cement or cementitious material in a mixture of fine aggregates and water. The other type is the utilization of crushed SiMn slag as a partial replacement for up to 50% of coarse aggregates in concrete production (Ganesh et al., 2018). The size of the crushed SiMn slag is recommended to be similar to gravel size for concrete production.

Raw manganese can be extracted from SiMn slag *via* two distinct methods. The physical method is the separation using crushed SiMn slag with particles ranging between − 500 μm and + 75 μm in a magnetic separator apparatus with a magnetic field of around 6,000 Tesla (Kim et al., 2011). The other method is a hydrometallurgical process based on the dissolution of Mn with sulfuric acid, leaching with lime slurry and KOH, and purification of leach solution with Na_2S at pH 5–7 electrodeposition by electrodes (Ayala and Fernández, 2015). Like air-cooled SiMn slag, the water-quenched SiMn slag can be reused in cement production. However, it must be heated and dried in an oven to remove moisture before being ground in a ball mill and mixed with cementitious materials. The slag can be incorporated into Portland Slag cement production by grinding 10 wt% water-quenched SiMn slags, 30 wt% blast furnace slag, and 60 wt% clinker (Nath and Kumar, 2016). For brick production, water-quenched SiMn slag is suggested for this purpose. The slag shall be crushed and heated in the oven at 110°C for 24 hours and subsequently used as aggregate in a cement, gravel, and water mixture. The mixture is then molded into bricks with a pressure of 5 MPa (Shao et al. 2017). The final product is the alkali-activated binder/cement produced from either type of SiMn slag. The slag must first be ground in a ball mill and blended with fly ash and Portland cement. Moreover, the alkali-activated binder/cement can be used to prepare mortar by another subsequent step which is mixing with an alkali-activator solution containing 27 wt% of 6 M NaOH (Nath and Kumar, 2017, 2019).

3.5. Recent challenges and future perspectives

Presently, only a few recycling practices are available to recycle and reduce the amount of SiMn slag. The water-quenching process produces mostly glassy and crystalline SiMn slag to produce other cement, mortar, and bricks. However, it incurs additional costs for water quenching plants and treatment. In addition, for reutilization of the SiMn slag, the technology such as current equipment and tools, including ball mill, oven, and crushers, is still limited and inappropriate for mass production of SiMn-slag-based products. Energy and cost must be considered for mass recycling of SiMn slag.

Several studies indicated that the mechanical strength of the SiMn slag incorporated mortar and concrete showed slow growth in strength up to 7 days; however, the strength can significantly increase from 28 to 90 days (Frias et al., 2006; Frías and Rodríguez, 2008; Nath and Kumar, 2016; Navarro et al., 2017). Thus, extra curing time is needed for the SiMn-slag-based mortar and concrete. Furthermore, high shrinkage values have also been detected, ranging from 1.5–3.0% (Navarro et al., 2017).

Although the current literature has revealed some success stories of SiMn slag reutilization into various construction materials, more studies must be addressed for future improvements, such as:

- To develop industry-level machines such as ball mill, oven, and crusher for large quantities of SiMn slag in the pre-treatment stage.
- To develop safe and environmentally friendly landfilling methods for disposing of SiMn slag.
- To study physicochemical characteristics from other countries, including chemical compositions, for more accurate analysis.
- To further investigate the feasibility and practicality of reutilizing SiMn slag in lightweight concrete production.
- To acquire more applications of SiMn-slag-based materials or products in actual projects to determine the practicality of the SiMn slag.

4. Conclusion

SiMn slag is a by-product of FeMn and SiMn alloy production in submerged electric furnaces. Due to the growing quantity of SiMn slag, a review on the physicochemical characteristics and its recycling applications as construction materials was conducted. Twenty articles were shortlisted and assessed to obtain information regarding the physicochemical characteristics and the recycling applications as construction materials.

According to the chemical compositions of five countries, namely China, India, Iran, Spain, and South Korea, the slag exhibits common oxides such as SiO_2, Al_2O_3, CaO, MnO, MgO, FeO + Fe_2O_3, and K_2O + Na_2O at similar quantities. Moreover, the recycling applications as construction materials were reviewed, such as binder/cement, brick, mortar, paste, concrete, backfill materials, and raw manganese material. Six critical governing factors that influence SiMn slag reutilization were identified, i.e., cooling methods, moisture, fineness, equipment, energy, and cost. Two cooling methods produce two different slags, namely air-cooled SiMn slag and water-quenched SiMn slag. The main difference between the two types is that water-quenched SiMn slag exhibits crystalline and is more brittle than air-cooled SiMn slag and requires additional heating. In addition, moisture affects the cement quality and production from SiMn slag. Slag fineness also affects its reactivity and determines the purpose of production. Lastly, equipment, energy, and cost are factors related to the scale of mass recycling of SiMn slag; thus, these factors must be considered.

Strategies to enhance SiMn slag reutilization have also been suggested in this review. The slag may undergo a pre-treatment stage such as reheating in an oven, crushing, or ball milling to reach a certain fineness or particle size. The processed slag undergoes one or more of the four physical/chemical treatments, i.e., mixing with cementitious material, water, sand, coarse aggregates, magnetic separation, hydrometallurgical process, and molding. Eight different SiMn-slag-based products are suggested, i.e., backfill material, cement, paste, mortar, concrete, raw manganese, brick, and alkali-activated binder.

The present challenges for SiMn slag reutilization include (but are not limited to) improper disposal of SiMn slag, insufficient recycling applications, additional costs for water treatment for water quenching, and inadequate industry-scale equipment for mass recycling. More attention must be paid to the growth of the strength of the SiMn slag during the initial 7 days of curing and the high shrinkage. Lastly, further studies are required on the development of industry-scale recycling applications, safe landfilling methods, SiMn slag properties from various countries, the practicality of SiMn-slag-based products, and the feasibility in actual projects.

Declarations

Ethical Approval

NOT APPLICABLE

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Consent to Participate

Consent from all authors have been taken and all authors are agreed on the provided content.

Author Contributions

All authors contributed to the study conception and design phase. Material preparation, data collection and analysis were performed by Jibril Adewale Bamgbade & Choo Ching Siung. The first draft of the manuscript was written by NgieHing Wong and Changsaar Chai all authors commented on previous versions of the manuscript. The draft is revised by Ali Raza Khoso and Ratanak Sambo. All authors read and approved the final manuscript.

Consent to Publish

All authors agreed to publish the data.

Availability of data and materials

All data is available in the manuscript.

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Figures

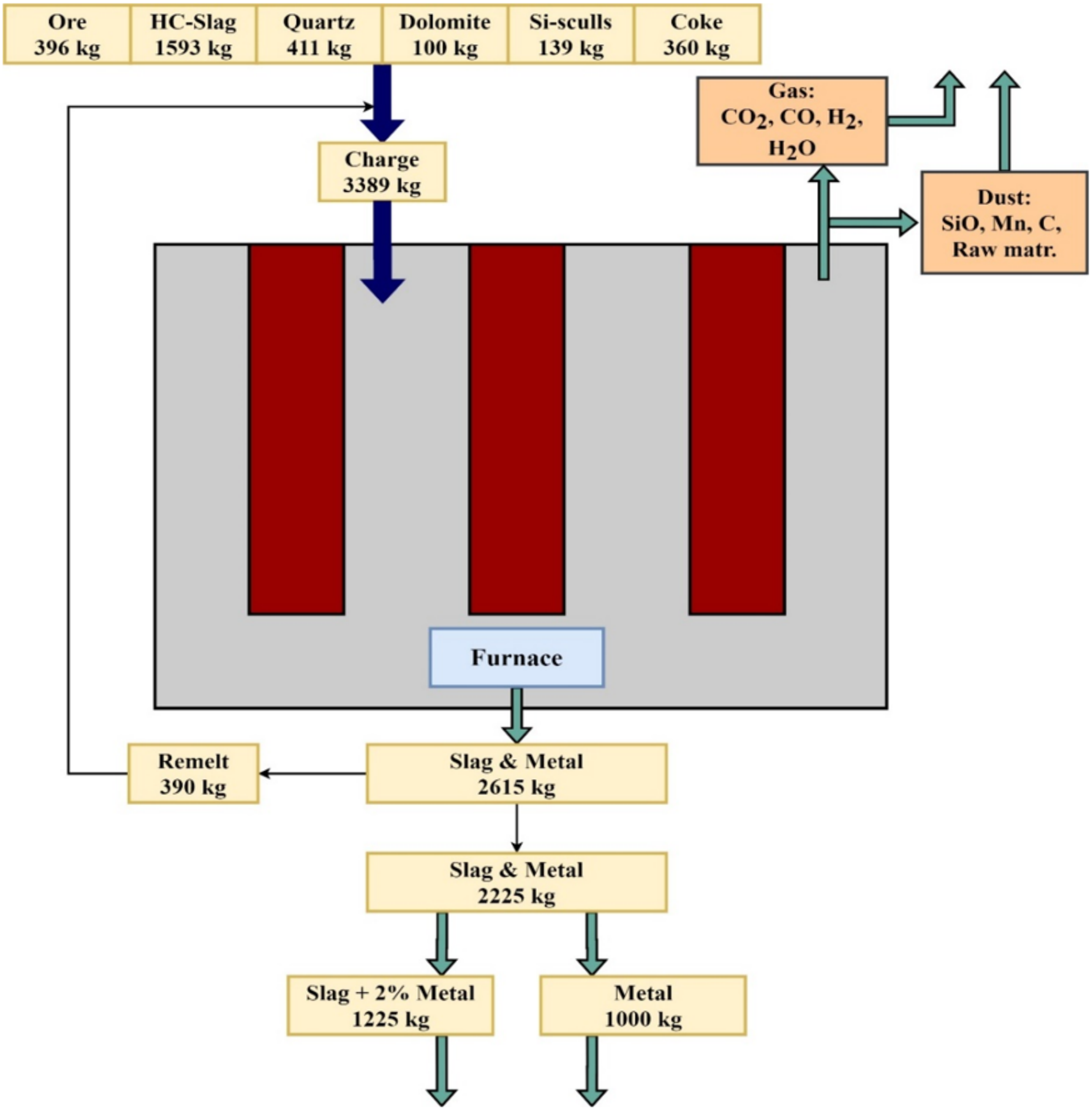

Figure 1

A schematic view of 3 tonnes of SiMn alloy production.

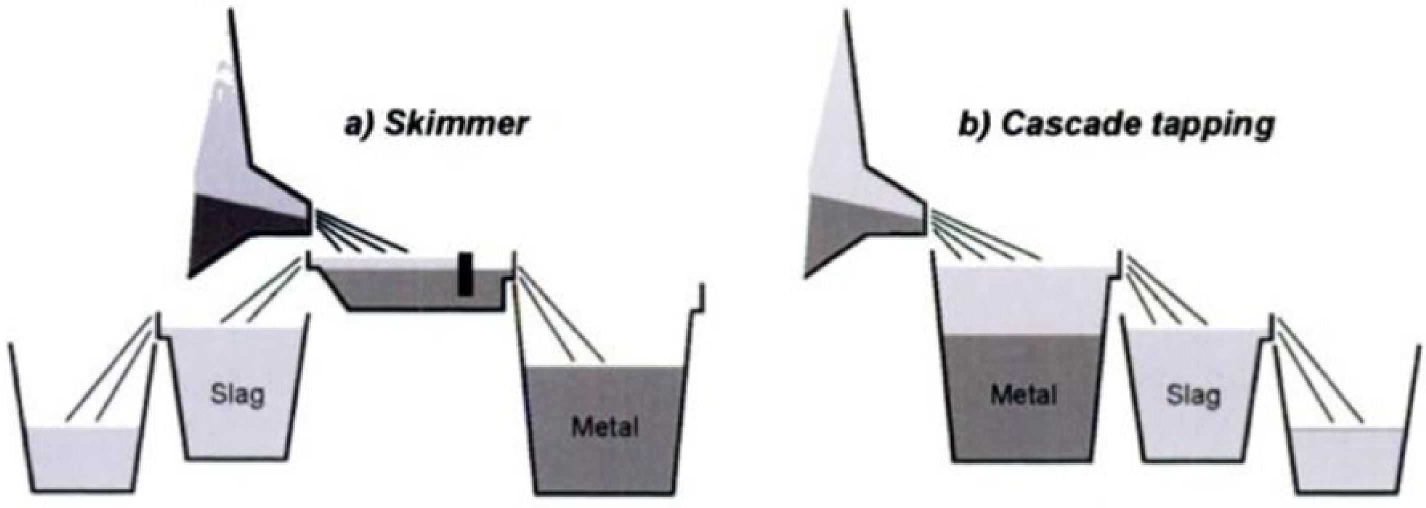

Figure 2

(a) Skimmer and (b) cascade tapping for slag and metal separation (Olsen Tangstad & Lingstad 2007).

Figure 3

Flowchart of the systematic review to collect articles for this study.

Figure 4

Flowchart of the systematic review with the number of articles collected.

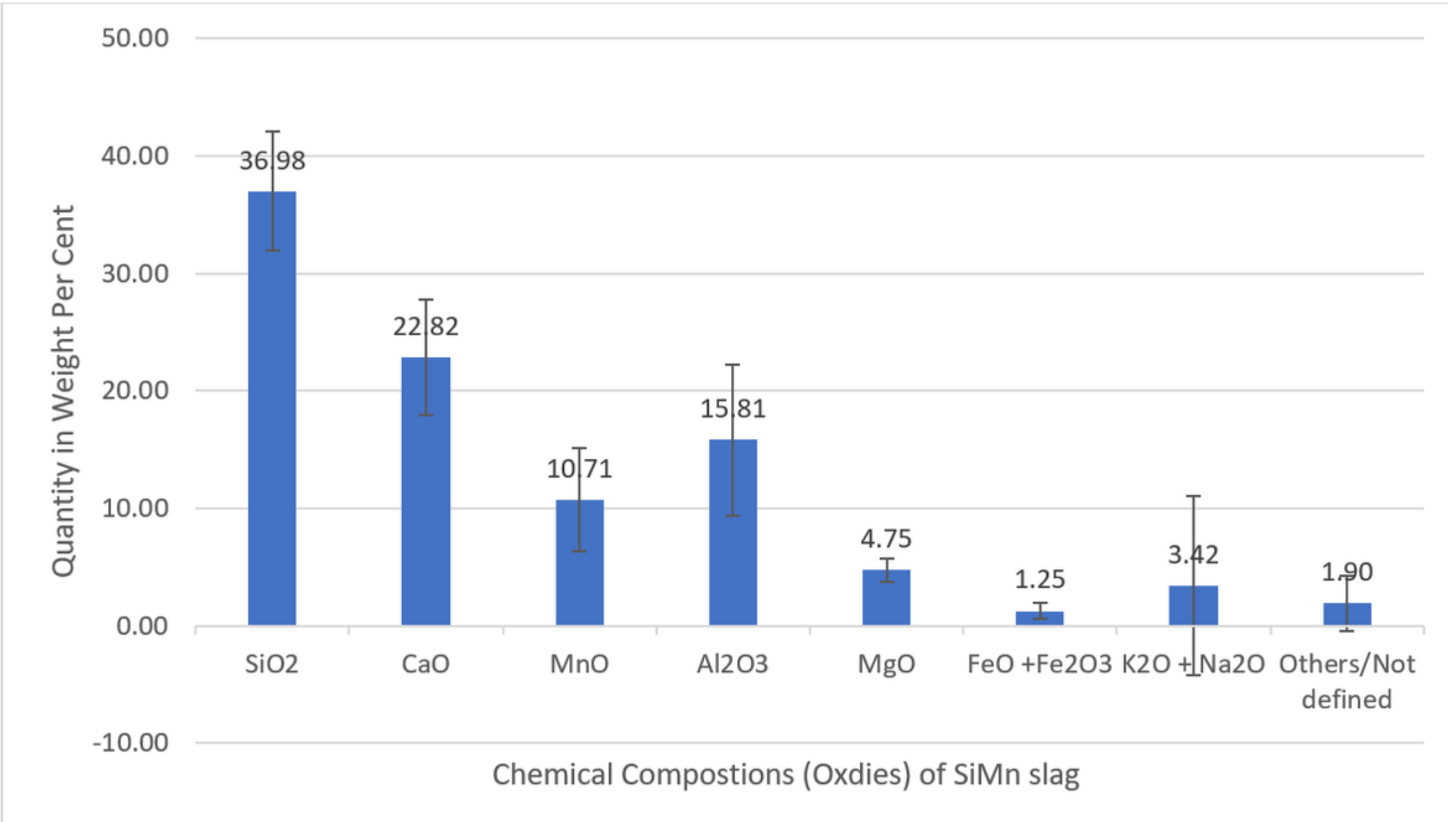

Figure 5

Chemical compositions of SiMn slag in average wt%.

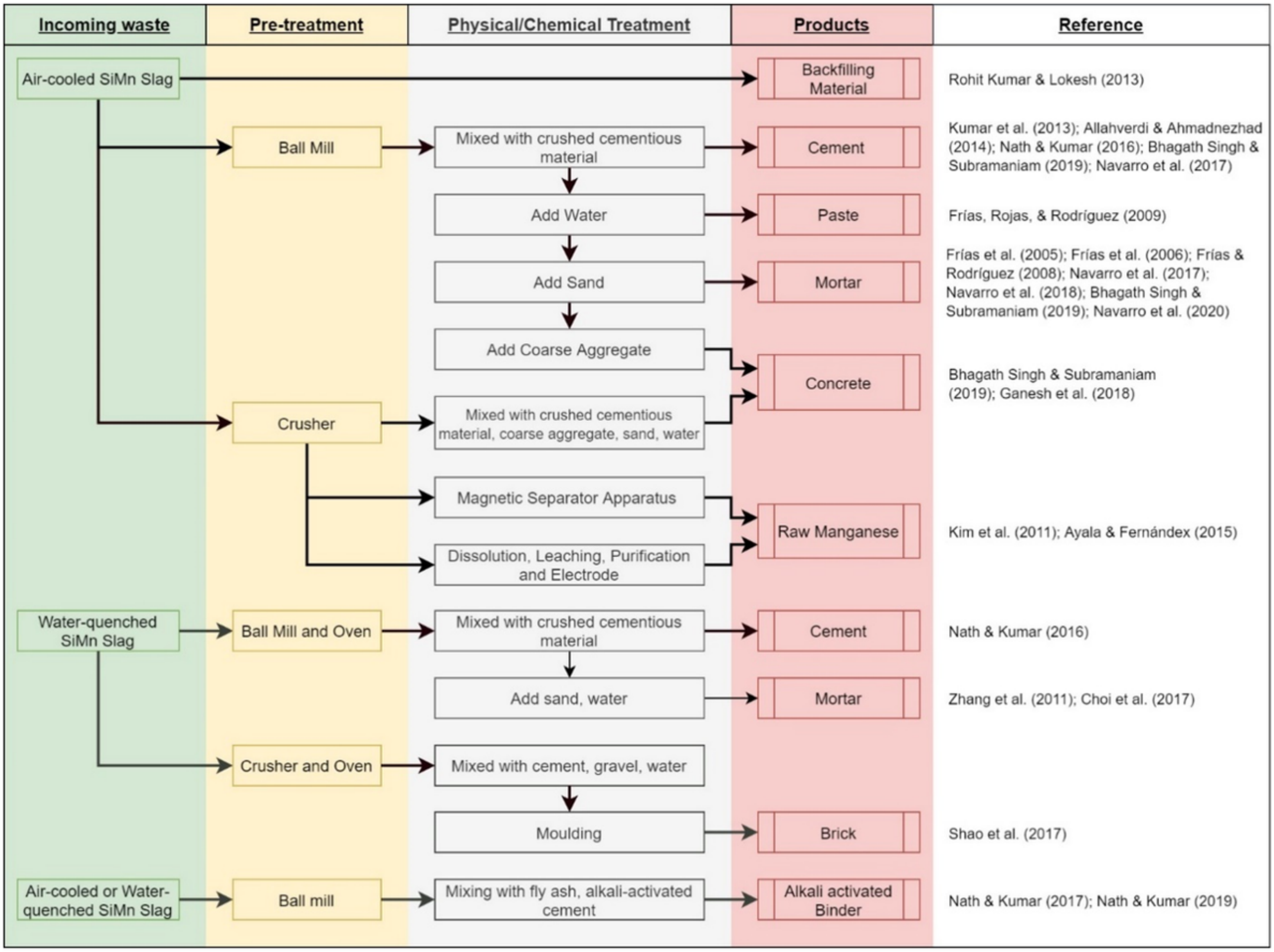

Figure 6

A conceptual process chart summarizes strategies to improve SiMn slag reutilization as construction materials.