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FEASIBILITY OF RECYCLING SILICOMANGANESE SLAG AS A CEMENTITIOUS MATERIAL

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Abstract: The rapid urbanization and industrialization of a country tends to generate large volume of industrial waste in the environment. In this sustainability era, feasibility of recycling industrial waste has gained attention by researchers and industry practitioners. Silicomanganese (SiMn) slag is a common industrial waste produced in the ferro-alloy smelting plant in Sarawak. This paper intends to present a review on the feasibility of recycling SiMn slag into a more sustainable construction material. A desktop study has been conducted to explore the feasibility of SiMn slag on its engineering aspects. Review indicated that SiMn slag is potential to be recycled as an alternative cementitious material. By replacing cement with SiMn slag, it will not only bring the positive impact on the economical aspect but also environmental aspect. This suggestion is critical in responding the call of Sustainable Development Goals (SDGs) of being responsible on the products consumption and production through promoting sustainable use of generated industrial wastes.

Keywords: Construction material; Industrial wastes; Sarawak; Silicomanganese slag; Sustainable.

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1. Introduction

With the rapid of industrialization, the production of waste and unsustainable materials has been increased significantly in the world. This has led to a significant contribution to the climate change. Ordinary Portland cement (OPC) is one of the most important common types of binder used for construction around the world (Bengar et al., 2020). Despite of having beneficial usage in various aspects in the construction, it is estimated that 7% of the entire human-related carbon dioxide (CO_2) is emitted into the atmosphere from OPC production (Taylor et al., 2006). Rapid industrialization also significantly increases the demand for steel which serves as another vital building material. Statistic shows that more than 50% of world steel demand are used in construction. However, to produce these steel productions not only release CO_2 but also generate tons of solid wastes, namely, slag, dust, sludge, debris, etc. Slag is the highest generated amount amongst these wastes (Kumar, 2019).

In Sarawak, it is reported that 400,000 tons of industrial waste (including SiMn slag) is generated and landfilled at the smelter in Bintulu's Samalaju Industrial Estate (Wong, 2018). Besides, it is estimated that 444,000 tons of SiMn slag will be generated from smelting activities at Samalaju Industrial Park in Bintulu per annum (“Dayak Daily,” 2022; “The Star,” 2012). The current disposal method, landfill will not only consume extra cost and land but it creates burden to the surrounding environment. Thus, it is crucial to discover a more sustainable and economical strategy to utilize or recycle industrial wastes.

Silicomanganese (SiMn) slag is an industrial waste generated through the production of silicomanganese alloy in submerged electric arc furnace (Kumar et al., 2013). Due to lack of awareness of its properties, SiMn slag is commonly disposed through landfill. SiMn slag has shown to be reactive, when it was disposed through landfill, it might become a source of environmental pollution in the past studies (Ayala & Fernández, 2015; Navarro et al., 2008). In addition, heavy metals can often be detected in the ground and groundwater areas especially Mn content (Ayala & Fernández, 2015; Navarro et al., 2008).

Silicomanganese (SiMn) slag has been considered as slightly reactive cementitious materials because of its low-solubility. The methods of cooling down the molten slag through water quenching and air quenching will form two different forms of slag, namely, granulated slag and lumpy slag. During the water quenching, the sprayed cold water will entrap in the molten slag and expanded rapidly (water become steam and expand rapidly) due to high heat of the molten slag. The cooling effect has produced glassy phase in the slag. In the air quenching, the surface of molten slag is cooled with air rapidly, however the inner side of slag cooled down slowly forming crystalline phases (Nath & Kumar, 2016). Granulated slag has a higher hydraulic activity as compared to lumpy slag which exhibit some latent hydraulic activities (Allahverdi & Ahmadnezhad, 2014; Zhang et al., 2018). In addition, the reactivity of SiMn slag is highly associated with its structure whereas the glassy phase, which is thermodynamically metastable is more reactive as compared to crystalline phrase.

SiMn slag has been suggested as an alternative material in various applications within the construction and engineering fields. For instances, SiMn slag has been implemented as sub-base material in road and rail track construction (Patil & Pande, 2011), as a photocatalyst (Zhang et al., 2018), in electroconductive geopolymer composite (He et al., 2019), as aggregate in concrete used in marine structure (Ting et al., 2020), as a sources of nano-silica (Namvar et al., 2020) and as binder in alkali activated mortar (Kumar et al., 2013; Najamuddin et al., 2019). Some scholars addressed slags constitute cementitious and pozzolanic properties and this has caused it to be a potential alternative material to substitute cement to reduce the economic and environmental impacts caused by cement production. As such, this paper attempts to highlight and discuss few selected and relevant recent studies on the potential usage of utilizing SiMn slag as cementitious material in the construction sector. Furthermore, the chemical composition of SiMn slag, the properties of SiMn slag cement concrete and microstructure study, and the potential application of SiMn slag are discussed in the following sections.

2. Chemical Composition of Silicomanganese Slag

Review of the past studies showed that the percentage of each chemical composition of different types of SiMn slag is varies. The major chemical compositions of SiMn slag are silicon dioxide (SiO_2), calcium oxide (CaO), aluminium oxide (Al_2O_3) and manganese oxide (MnO) as illustrated in **Table 1.** These compositions are similar to those found in blast furnace slag (Nath & Kumar, 2016). The major chemical constituents namely, CaO, SiO_2, Al_2O_3, and MnO are typically comprised more than 70% of the total composition (Kumar et al., 2013). Additionally, SiMn slag is defined by its significant percentage in manganese content with the MnO content ranges between 6 to 10% (Ayala & Fernández, 2015; Frias et al., 2006).

Silicomanganese (SiMn) slag is typically richer in SiO_2 as seen from **Table 1**; whilst less CaO content than blast furnace slag (BFS) (typically > 43.7%). The presence of MnO in SiMn slag of which 5-10 wt% (percentage by weight) tends to reduce the content of CaO which caused the difference between BFS. This resulted in low hydraulic moduli (C/S) (0.6 - 0.75) compared to BFS (1 – 1.22) (Nath & Kumar, 2016). The moduli C/S is expressing the principal hydration product of hydrated OPC cement and the main component (C–S–H, calcium–silicate–hydrate) responsible for the strength of Portland cement-based concrete (Kunther et al., 2017). Hydraulic moduli C/S more than 1 is classified as basic and it is considered to have good reactive properties; whereas the hydraulic moduli C/S less than 1 is categorized as acid. Thus, blast furnace slag has been extensively adopted as cementitious material in manufacturing Portland slag cement, whilst SiMn slag did not get much attention as cementitious material.

Table 1. Chemical composition of SiMn slag

References	**Chemical Composition (%)**						**Moduli**
	CaO	**SiO_2**	**Al_2O_3**	**MnO**	**MgO**	**Fe_2O_3**	**C/S**
Nath & Kumar (2016, p. 129)	26.17	40.33	14.55	10.06	5.74	0.75	0.65
Allahverdi & Ahmadnezhad (2014, p. 42)	29.30	38.17	14.78	10.29	2.77	1.79	0.77
He et al. (2019, p. 1477)	21.86	28.34	18.45	11.58	4.72	0.72	0.77
Ting et al. (2020, p. 03)	21.04	41.49	13.95	8.12	4.61	4.47	0.51
Namvar et al. (2020, p. 03)	29.30	38.20	14.80	10.3	2.77	1.79	0.77
Frias et al. (2006, p. 488)	25.20	42.60	12.20	9.90	4.20	1.00	0.59
Rai et al. (2002, p. 491)	14.00	39.00	9.63	15.00	11.50	0.23	0.36
Choi et al. (2017, p. 376)	20.00	32.30	16.10	20.40	4.55	0.30	0.62
Wang et al. (2021, p. 03)	17.99	36.97	18.38	9.84	8.51	0.11	0.49
Zhang et al. (2011, p. 235)	17.14	29.02	25.01	4.65	5.59	0.81	0.59

3. Engineering Properties of Silicomanganese Slag

3.1 Pozzolanic Activity

Frias et al. (2006) investigated the pozzolanic activity of SiMn slag with reference to the fixed lime content variation. He observed that the pozzolanic activity of SiMn slag demonstrates intermediate reaction which is between fly ash (FA) and silica fume (SF) in the curing period of 28 days. SiMn slag consumes an insignificant amount of lime after 28 days of curing, and at 90 days of curing only 55% of the total lime was consumed. As a result of these findings revealed that pozzolanic activity of SiMn slag mainly occurs within 28 days.

3.2 Setting Time

Frias et al. (2006) observed that the incorporation of SiMn slag into the cement paste did not adversely affect the setting time. Cement pastes containing 5% and 15% SiMn slag showed similar initial and final setting times compared to the control cement paste. In contrast, Allahverdi & Ahmadnezhad (2014) observed that the increase in SiMn slag will increase both initial and final setting times. Nevertheless, he discovered that to decrease the setting times by increasing Blaine fineness is effective at a constant replacement level. However, with the 35% of SiMn slag, the initial setting and final setting was still able to fulfill the standard requirements in the Standard Specification for Portland Cement, American Society for Testing and Materials (ASTM) C150. In contrast, Zhang et al. (2011) discovered that the initial setting time of sample incorporated with 80% of SiMn slag is 5 min shorter than the Ordinary Portland Cement (OPC), which is 11% faster. Besides, the final setting of sample incorporated 80% SiMn slag shows a significant reduction as compared to OPC.

3.3 Volume Stability

Frias et al. (2006) studied the volume stability of SiMn slag in cement paste by carried out the expansion tests according to European Standard, EN196-3:1994, Methods of Testing Cement. From the results, it is observed that SiMn slag blended cements do not change the values of the expansion, therefore SiMn slag blended cements is shown to be volume stability. This conclusion had been agreed by Allahverdi & Ahmadnezhad (2014). Moreover, Allahverdi & Ahmadnezhad

(2014) observed that neither replacement level of SiMn slag and Blaine fineness of SiMn slag will play a crucial role in measuring the values of expansion.

3.4 Mechanical Strength

Péra et al. (1999) performed the tests using blast-furnace slags collected from different areas with manganese oxide (MnO) content up to 21%. This study first discovered that the MnO in the slag might result in a low early strength (3 days to 7 days). However, it does not affect the compressive strength at 28 days (Péra et al., 1999). In this study, a minimum compressive strength at early stage has been achieved by the mortar cast with 21% of MnO but obtained the best long-term strength. Nevertheless, the relationship between the content of MnO and the pozzolanic reactivity of the slag has not been explained.

Rai et al. (2002) studied the feasibility of using metallurgical slags with high MnO and low MnO in producing blended slag cements. They observed that with the composition of 50:50 blend using granulated slag with low MnO content, grounded to $300m^2$/kg (Blaine Fineness), was found to satisfy Indian Standard for Portland slag cements. Nonetheless, they reported that high MnO slags have deleterious effects in blended cement. Thus, it is not considered suitable for slag cements.

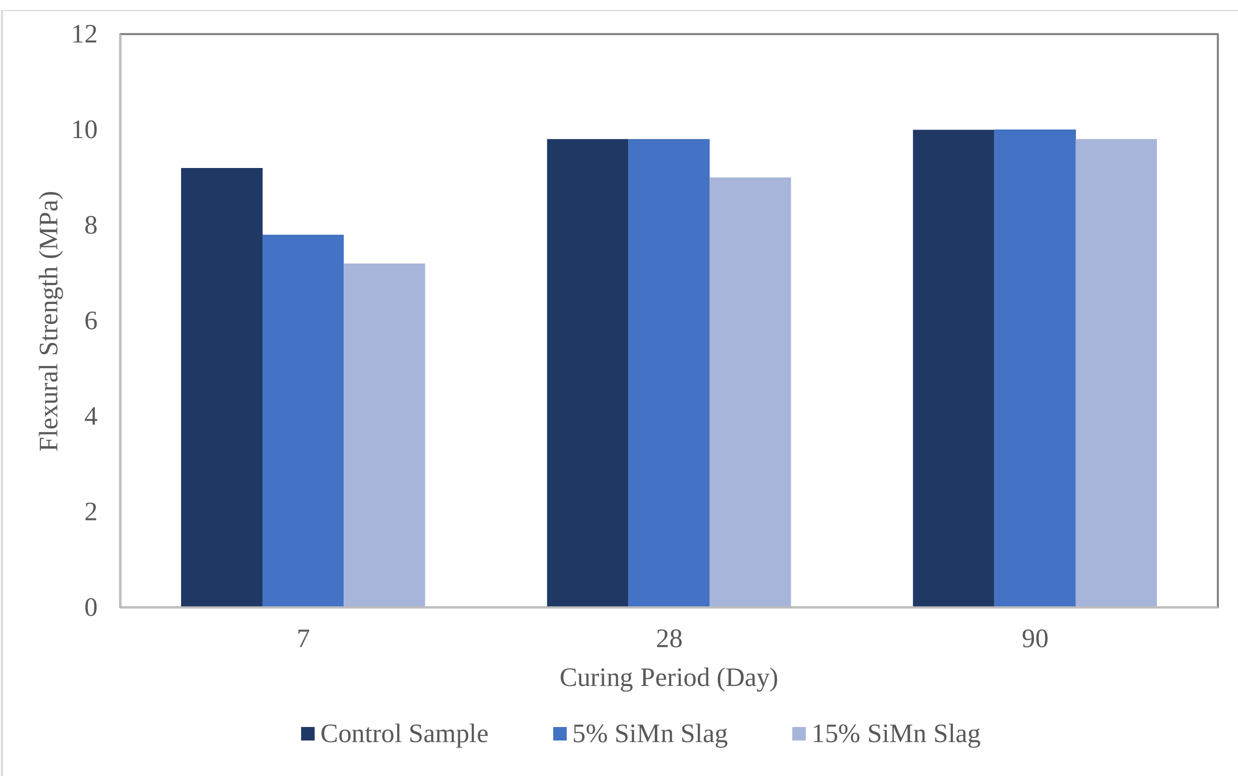
Frias et al. (2006) carried out a systematic laboratory test on the feasibility of using SiMn slag as cementitious material in blended cement. The SiMn slag sample exhibits a lower flexural strength compared to control samples, whereas the higher the SiMn content, the lower the flexural strength. Nevertheless, the flexural strength of the sample increased significantly after 7 days, and achieved a similar flexural strength to the control sample after 28 days of curing; however, at 90 days of curing, the flexural strength of the control sample and the 5% SiMn slag sample was similar. As shown in **Figure 1(a)**, the sample with 15% SiMn slag also had a flexural strength within 5% of the control sample. In terms of compressive strength, the addition of SiMn slag led to a slight decrease of the strength value for the first 28 days after curing. After 90 days of curing, the compressive strength values of the SiMn slag sample were very similar to those of the control mortar. **Figure 1(b)** shows that the compressive strength values of the 5% SiMn slag at 90 days are identical to those of the control sample. Due to its low hydraulic reactivity, SiMn slag can reduce the early strength of cement mortar. Hence, improvement of hydraulic properties of SiMn slag through mechanical activation become a trend of the study (Allahverdi & Ahmadnezhad, 2014).

Han & Gao (2004) conducted the first study to examine the effect of mechanical activation on hydraulic properties of SiMn slag by experimental program. Silicomanganese (SiMn) slag samples were ground in the ball mill at the time of 10, 20, and 40 minutes and added into the mortar specimen to replace 30% of cement content. He found that the grinding period is positively associated with the strength development of the mortar specimen. After 28 days of curing, by increasing the grinding time from 10 to 40 minutes, the tensile strength of the specimen increased dramatically from 4.31 MPa to 7.85 MPa; a similar outcome has been obtained on compressive strength. As compared to the specimen with 10 minutes of grinding, the specimen with 40 minutes of grinding increased in tensile strength and compressive strength by 82% and 126%, respectively. Moreover, the specimen with 30% cement replacement and 40 minutes of grinding exhibited similar tensile strength and compressive strength to cement mortars without SiMn slag. This study suggested that SiMn slag can be used as a replacement in Ordinary Portland Cement (OPC) through mechanical activation. This study, however, does not standardize the grinding process of SiMn slag in terms of fineness.

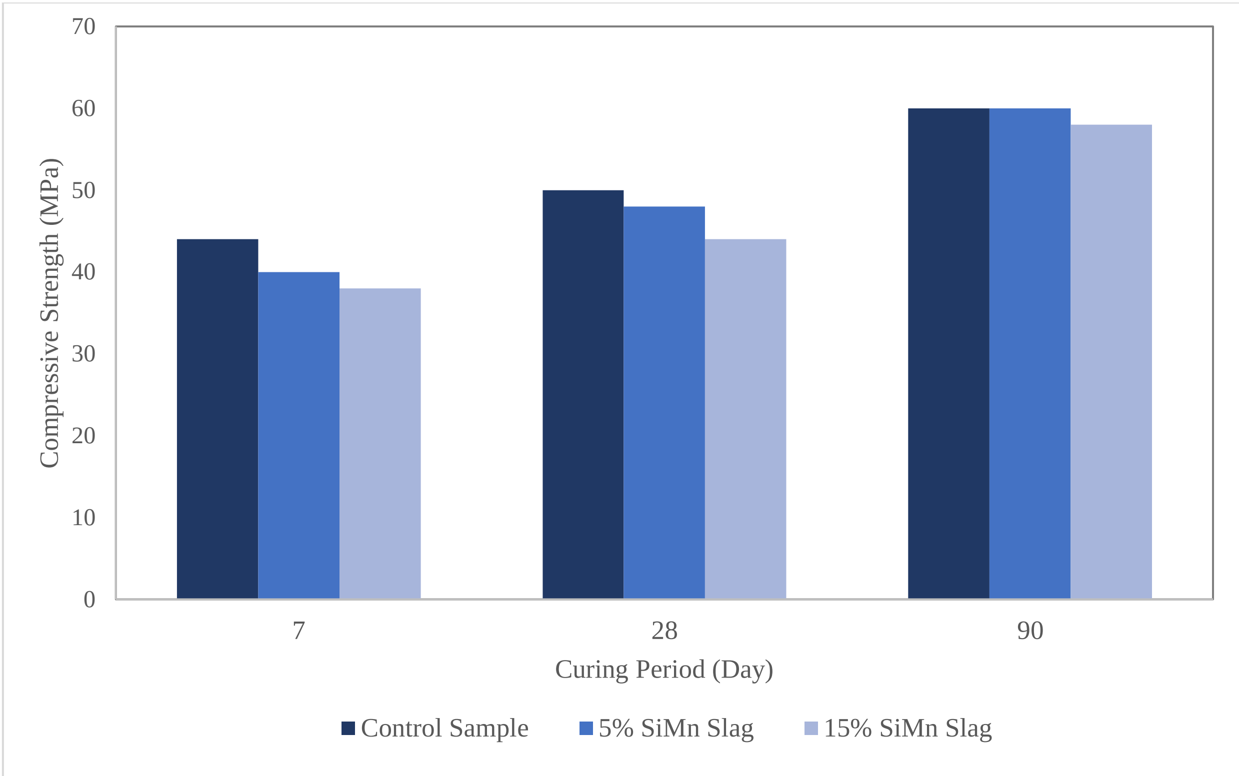
Prompt to this background, Allahverdi & Ahmadnezhad (2014) studied the mechanical activation of SiMn slag on the improvement of hydraulic properties. These air-cooled SiMn slags were ground into various Blaine specific surface areas, namely, 290 kg/m^2, 330 kg/m^2, 370 kg/m^2, 410 kg/m^2. The SiMn slag was added to replace Portland cement at the maximum content of 35%. The mechanical activation of cement specimens proved effective in improving their strength in laboratory tests. Hence, he found that raising Blaine fineness to higher values enables a higher substitution of SiMn slag in cement. For instances, it was observed that at the Blaine fineness of 410 kg/m^2, a substitution level of 35% SiMn slag can still achieve a 28-day compressive strength above the optional limit in accordance with ASTM.

On the other hands, Nath & Kumar (2016) investigated to replace blast furnace slag in Portland slag cement with granulated SiMn slag. Nath & Kumar (2016) discovered that the glass phase of SiMn slag helps to improve the hydration reactivity in the cement. He explained that the glass phase is thermodynamically metastable and more reactive than crystalline phase. The results showed that partial replacing cement with SiMn slag in concrete could achieve comparable compressive strength as compared to normal concrete at 28 days of curing. However, low early strength has been observed in the early curing period which are in-line with the results obtained by previous study (Frias et al., 2006). The early strength reduction is related with the formation of short length C-S-H and some non-hydraulic phases that occurred when replacing cement with SiMn slag. Nevertheless, the compressive strength of sample incorporated SiMn slag reduced at all curing stage as compared to blast furnace slag. This is due to blast furnace slag has a higher Ca/Si ratio which can be dissolved faster and react hydraulic reaction in the cement system.

Zhang et al. (2011) also investigated the hydration mechanism of granulated SiMn slag. Worth noting cement incorporating SiMn slag exhibited superior flexural strength and compressive strength when compared to Ordinary Portland Cement (OPC) at 28 days of curing. The flexural strength and compressive strength of SiMn slag-based cement were found to be 8.8 MPa and 51.5 MPa, respectively, whereas OPC had the flexural strength and compressive strength of 6.5 MPa and 42.5 MPa. This is due to existing Al^{3+} and Si^{2+} content in SiMn slag will improve the hydraulic reactivity in the cement system. The hydraulic mechanism of these element will explain details in the section below.



(a)



(b)

Figure 1. (a) Flexural strength of SiMn slag mortar (b) Compressive strength of SiMn slag mortar (modified from Frias et al., 2006, p490)

3.5 X-ray Diffractometry

Allahverdi & Ahmadnezhad (2014) studied the X-ray diffractograms (XRD) for hardened stage of cement paste with the mixes of 15% SiMn slag. From the results, they observed that the presence of Gehlenite, which is a non- or very low hydraulic crystalline phase, as main crystalline phase in SiMn slag-cement paste. In addition, Gehlenite is a crystalline phase that can usually be found in industrial waste. Furthermore, they found that the Portlandite's characteristic peaks of both SiMn slag-cement paste increased with curing time after 7 days of curing period. This shows that SiMn slag exhibits hydration reaction quickly in cement blended. Zhang et al. (2011) discovered that the ettringite crystallizes grow continuously from 3 days to 28 days of curing. This indicated that large amounts of amorphous and low-crystalline substance exist in the hydration products of 7 days and 28 days of curing.

3.6 Scanning Electron Microscope Studies

Allahverdi & Ahmadnezhad (2014) studied the microstructure of cement sample incorporated with SiMn slag through Scanning Electron Microscope (SEM). It was confirmed the different microstructural morphologies between specimens incorporating 15 wt.% SiMn slag and plain cement paste (without SiMn slag); where the microstructure of specimens incorporating SiMn slag involves small non-reacted slag particles. The unreacted SiMn slag particles in the hydration products were readily observable using backscattered secondary electrons mode of the microscope, as revealed in the SEM image. This presence of unreacted slag particles was found to contribute to a reduction in strengths. Nevertheless, the presence of gehlenite, in the SiMn slag is also responsible for the strength loss. In contrast, Zhang et al. (2011) did not observe SiMn slag particles obviously in the specimen after 28 days of curing. In addition, the SiMn slag used in his study is granulated slag obtained through rapid cooling. This phenomenon is due to most of the SiMn slag particles have been transformed into new substances after longer curing time.

3.7 Water Absorption and Open Pore Volume

Allahverdi & Ahmadnezhad (2014) found that total open pore volume and water absorption increased with the replacement level of SiMn slag. This was attributed to the pozzolanic and latent hydraulic properties of SiMn slag cement, which showed dissatisfaction in microstructural densification during 28 days of curing. Nevertheless, Ting et al. (2020) showed that SiMn slag reduced the water absorption and open pore volume when it was used as coarse aggregates in concrete. This is because SiMn slag possess a lower water absorption compared to limestone aggregates and therefore resulted in the reduction of water absorption of the concrete samples. This revealed that reduction of water absorption in SiMn slag-based concrete was also due to the reduced porosity in the concrete caused by the use of SiMn slag as coarse aggregates.

3.8 Hydration Mechanism

Review of literature discovered that the early strength reduction has been observed in replacing cement with SiMn slag. This is due to SiMn slag is commonly low in Ca/Si ratio, typically lower than 1 which is difficult to dissolve in the cement system (Frias et al., 2006; Nath & Kumar, 2016). However, the hydration reaction of SiMn slag tends to be accelerated with the growing curing period. This phenomenon is due to the Al^{3+} ions decomposed from SiMn slag glassy network combined into ettringite quickly in the presence of Ca^{2+}, SO_4^{2-}, $OH^-$and H_2O (Zhang et al., 2011). Ettringite crystallization can consume Al^{3+} immediately and thus make the Al^{3+} unsaturated leading the decomposition of Al^{3+} from the glassy network (Zhang et al., 2011). As more $Al^{3+}$is decomposed, the residue Si–O network becomes looser, and more surface is exposed to the attack of OH^- and other ions. A large amount of Si–O tetrahedral network is depolymerized after the attacking of OH^- and other ions. It provides a favorable condition for the formation of a large amount of C-S-H (hydrated calcium silicates) gel in the cement system (Nath & Kumar, 2016; Zhang et al., 2011). Furthermore, the decomposed Al^{3+}may enter C-H-S gel in the structural state of tetrahedral coordination and form Al_2O_3-containing tetrahedral network (Zhang et al., 2011). The increase amount of C-S-H gel and Al_2O_3-containing tetrahedral network will improve the strength of the sample.

3.9 Leaching Properties

As listed in **Table *1***, it is worth noting that the residual of MnO content in SiMn slag is generally exceeded 5wt%. Some of the SiMn slag consists more than 20% of MnO. This might lead to environmental pollution due to Mn leaching. Therefore, it is important to study the heavy metal ions leaching behaviour of SiMn slag when used it as cementitious materials. According to Marion et al. (2005), the leaching of heavy metals is negligible when substituting cement with blast furnace slag. The levels of heavy metal leaching were found to be well below the regularity limits set by United States Environmental Protection Agency (EPA). Furthermore, the substituting materials such as blast furnace (BF), electric arc furnace (EAF) slag and basic oxygen steel (BOS) also showed that the leaching of heavy metal are below the regularity limits (Proctor et al., 2000). Frías et al. (2009) discovered that the cement mortar incorporated 15% SiMn slag has a good chemical resistance when served in aggressive solution such as sodium sulphate, sodium chloride and seawater. The cement mortar incorporated SiMn slag did not experience significant weight variations when submerge in aggressive solutions after 56 days. This is due SiMn slag modify and refine the porous structure of cement mortar. The matrix of cement becomes denser and more durable after the refinedness process. Liu et al. (2022) observed that the leaching concentrations of heavy metals of SiMn slag-based mortar such as Cu, Pb, Cr, Cd, Ni are lower than the limits based on the Chinese standard. However, the leaching concentration of Mn are exceeding the limit. This phenomenon is due the granulated slag obtained from rapid cooling used in this study has more glass phase in the slag. Although glassy phase content will increase the hydration reactivity in the cement sample, the glassy phase is easy to be dissolved in alkaline conditions which lead to the leaching of Mn. The glassy phase of SiMn slag in the cement system could be attacked by $Ca(OH)_2$ and form $Mn(OH)_2$ which could further be dissolved by acid and caused Mn leaching. Nevertheless, the Mn leaching of SiMn slag in normal service environment is extremely restricted by cement hydration.

4. Potential Application

Numerous studies have been conducted to investigate SiMn slag as partial replacement for cement in concrete. Rai et al. (2002) shows that SiMn slag at 50% replacement level of cement can achieve the strength identical for Portland Slag Cements and 33MPa Ordinary Portland Cement in Indian Standard (IS). However, there is a significant strength loss at early and late stage compare to the original Portland Cement. Frias at al. (2006) found that SiMn slags have a good rheological behavior which pozzolanic activity are intermediate between silica fume and fly ash. At a small amount cement replacement with SiMn slag in blended cement (5% - 15%) does not significantly reduce the compressive strength. In fact, the compressive strength of cement with 15% SiMn slag of blended cement sample is nearly identical to the control sample at 90 days of curing, though there is an obvious strength reduction at the early strength. This early strength reduction is mainly attributed to the limited pozzolanic reaction during the early stage. This phenomenon is also observed by Nath & Kumar (2016) in exploring the effect of replacing blast furnace slag with SiMn slag in Portland Slag Cement. Nath & Kumar (2016) demonstrated that the use of SiMn slag as partial replacement for cement could achieve similar compressive strength at 28 curing days as compared to original Portland Slag Cement. Besides, Allahverdi & Ahmadnezhad (2014) investigated the influence of SiMn slag on the properties of Portland Slag Cement using mechanical activation method. Experimental results have proven that mechanical activation was effective in incorporating SiMn slag as partial replacement of cement up to 35% without significant changes in setting times. Moreover, it is possible to counter the loss of mechanical strength at the early stage by increasing the Blaine Fineness.

Nevertheless, the existing research data on utilizing SiMn slag as cementitious materials are collected through laboratory scale study. Limited samples are prepared, tested, and characterized in these investigations. These data collected may not reflect the durability and performance consistency in actual conditions. Moreover, some important parameters such as skid resistance and abrasion resistance of SiMn slag-based cement products have not been studied yet in the literature. Besides, the economical aspect of utilizing SiMn slag as cementitious materials have not been presented. Thus, pilot scaling of the process, performance mapping, and life cycle environmental analysis as well as life cycle cost analysis are crucial for its standardization as well as implementing feasible processes.

In spite of having potential to utilizing SiMn slag as cementitious materials, the current technology is still not sufficient to apply it in the industrial. The major constraint is due to the quality of the slag such as chemical composition, glassy content, and crystalline phase that produced by varies manufacturing industries in different region is inconsistent. The chemical composition, glassy content, and crystalline phase of the slag is important in the strength development of cement products. Therefore, quality control of SiMn slag production is necessarily to utilize it as cementitious materials in cement products such as concrete for structural. In order to maintain the quality of SiMn slag, the manufacturing industries must follow certain recognize standard procedure. Furthermore, the manufacturing industries must the existing practice of air-cooling process of the molten slag. As the granulated SiMn slag from rapid cooling is proved to be more reactive due to it glassy content through literature. The granulated slag provides significant strength development in all stage of curing as compared to lumpy slag from air cooling. Thus, granulated slag is said to be more idealize cement supplementary materials as it minimizes the negative impact that may cause by replacing cement with SiMn slag. Nevertheless, the manufacturing cost of air cooling is comparably higher than rapid as early mentioned. Thus, there must be some worldwide standard, strategy or government policy to regulate these manufacturing industries to produce granulated SiMn slag that follow certain standard procedures. Silicomanganese (SiMn) slag can be a valuable by-product for cementitious applications if the SiMn manufactures and their stakeholders, scientists, technologists, and civic bodies, work together to address the above gap and overcome these limitations.

5. Economical Beneficial

As early mentioned, the granulated SiMn slag from rapid cooling method is more reactive and idealise as cementitious material. In addition, rapid cooling method (water quenching) will increase the manufacturing cost as water quenching process required additional labour, equipment, and water treatment plant (Nath & Kumar, 2016). However, the increment of cost can be compensated by high reactivity of the slag. Besides, the granulated slag obtained from water quenching process is mostly glassy and porous which required less energy to mill the slag before used it as cement supplementary materials (Nath & Kumar, 2016). Furthermore, if SiMn slag can be successful applied as supplementary cementing materials in Ordinary Portland cement (OPC), the manufacturing cost of all cement related products has a high tendency to reduce. Cement is the most expensive material in concrete production (Lovato et al., 2012). In addition, the price of cement will be increased twice in 2030 if carbon emissions are beyond the limit (OECD/IEA and World Business Council for Sustainable, 2009). Thus, it is critical to explore the economical aspect of replacing cement with SiMn slag.

6. Future Study

The future prospects for the utilization of SiMn slag are developing the binary and ternary concrete incorporating SiMn slag with others industrial wastes such as silica fume and fly ash. Results of the literature review showed that SiMn slag will reduce the early strength of the specimens. In contrast, silica fume is known to increase the early strength performance as well as the durability properties of the specimen (Meddah et al., 2018). This is due to the higher surface area and high proportion of amorphous silicon dioxide (SiO_2) (Meddah et al., 2018). Therefore, the silica fume could anticipate to minimize the adverse effect that caused by the presence of SiMn slag in cement blended. Besides, the cooling method of the molten slag can greatly alter the chemical composition and mineralogy of SiMn slag which will later affect the performance of SiMn slag-based cement.

Thus, it is important to investigate and standardized the cooling method of molten slag that can improve the reactivity of the slag to the greatest extent. Another approach is modifying the slag chemistry through hot stage engineering. The lime is added into the molten slag during the hot stage engineering in order to improve the Ca/Si ratio. On the other hands, there is potential of heavy metal leaching of SiMn slag-based cement products and caused environmental pollution. Though it is proved to be safe in the normal service condition (Liu et al., 2022), there is an environmental pollution concern due to the acidic or alkaline condition. Hence, it is crucial to reduce the Mn content in SiMn slag during the production. The possible solutions are increasing the efficiency of metallurgical process or recover the manganese from SiMn slag. Further study is required to study the environmental effect that might be caused by SiMn slag-based cement.

7. Conclusion

This paper reviewed the effects of utilizing SiMn slag as cementitious material on the properties of cement of few selected peer-reviewed papers. Based on the review, a few main findings have been concluded as below.

i. The major chemical compositions of SiMn slag are CaO, SiO_2, Al_2O_3, MgO and MnO with the MnO content ranges between 6% to 10%. Furthermore, the moduli C/S of SiMn slag is around 0.6 - 0.75 which is categorized as acid.

ii. The pozzolanic activity if SiMn slag is intermediate between FA (fly-ash) and SF (Silica Fume) during the first 28 days of curing. Besides, SiMn slag does not show any negative impact on the volume stability and setting time.

iii. From the technical perspective, it is feasible to utilize SiMn slag as a cementitious material in blended cements for improvement in mechanical strength. By increasing the blaine fineness of SiMn slag, the SiMn slag replacement level can further increase with minor strength loss. The content of $Al^{3+}\ and\ Si^{2+}$ also play a crucial role in strength development.

iv. From the economic perspective, it is expected that the SiMn slag replacement in blended cement will reduce the manufacturing cost of cement and its related products. This is due to cement is the most expensive material in producing these products, Furthermore, the price of the cement will increase twice in 2030 which gives an advantage of replacing cement content by SiMn slag.

v. The heavy metal leaching behaviour of SiMn slag in blended cement is within the limits stated in Chinese Standard in normal service environmental. However, the leaching of Mn has exceeded the limits when service in acid or alkaline environmental. The leaching of Mn may cause environmental pollution. Thus, further investigation is required to study and reduce the potential of Mn leaching before utilizing SiMn slag as cementitious materials.

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