Chapter 3
Co-Utilization of Slag By-products from Steel Industries in Sustainable Concrete

Mohammed K. H. Radwan, Yi Zhi Hoo, Jerome Song Yeo, Chiu Chuen Onn, and Kim Hung Mo

Abstract The global consumption of natural aggregates and cement is rising at an alarming rate due to the vast growing in construction industry. At the same time, the steel industries are generating large amounts of by-products in the form of electric arc furnace (EAF) slag, ladle furnace (LF) slag and ground granulated blast furnace slag (GGBS). These slag by-products can potentially be reused and utilized as partial substitute of the common constituent materials in concrete such as the aggregates and cement. This chapter thus investigates the influence of using the local EAF and LF slags as 40% aggregate replacement along with the GGBS at 25% cement replacement in concrete. The results demonstrated that improvement in the properties of concrete (such as compressive strength, water absorption, surface resistivity and mass changes) can be achieved with EAF slag as partial coarse aggregate replacement, and these properties can be further enhanced with the use of GGBS. This points towards potential of the co-utilization of the EAF slag and GGBS in a sustainable concrete mixture to maximize the use of these industrial by-products.

Keywords Electric arc furnace slag · Ladle furnace slag · Ground granulated blast furnace slag · Waste recycling · Sustainable concrete

3.1 Introduction

Natural aggregates such as crushed granite and gravel are commonly used in concrete. The availability of natural aggregates is fast depleting due to the growth in the construction industry around the world as a result of continuous development [1].

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For instance, the production of natural aggregates in Europe alone reached a new height of 4.33 billion tonnes in 2017 compared to 3.69 billion tonnes 4 years prior to that [2]. Cement, on the other hand, is manufactured in amount exceeding four billion tonnes in recent years, and the greenhouse gases (CO_2) liberated during its production phase that involves chemical and thermal combustion contribute to 4–6% of the CO_2 discharge worldwide [3]. In addition to greenhouse gas emissions, it is depleting natural resources at an alarming rate and involving an alteration in landscape as the raw material production rate ascends, thus violating the rule of sustainability [4]. Hence, alternative aggregates and partial cement replacements have since been sought in the form of construction and demolition waste [5], tyre waste [6] and agricultural wastes [7, 8], among others, to reduce the environmental burden [9].

On the other hand, steel industry that is growing has seen high output of steel products accompanied by huge amounts of by-products. Steel industry is recognized as the largest industry in terms of energy consumption. According to Conejo et al. [10], the demand for crude steel has been increasing since the early nineteenth century demonstrated by a significant increase in the production rate. Since 1900, the steel industry exhibited an exponential growth with about 3.4% per year [11]. Correspondingly, the emission increased substantially from around 0.22 Gt CO_2-eq in early 1900 to about 3.7 Gt CO_2-eq in 2015. The by-products include steel furnace slag (SFS) and blast furnace slag (BFS), which are generated in different steelmaking processes but generally when molten iron ore is separated from impurities [12]. Due to the immense heat involved in steelmaking, the slag first presents in the form of molten liquid melt containing silicates and oxides before it solidifies to form rigid aggregate upon cooling [13]. Granulated blast furnace slag is a type of BFS remaining from operations in the blast furnace, which turns into ground granulated blast furnace slag (GGBS) upon grinding [14]. Electric arc furnace (EAF) slag, meanwhile, is a type of SFS that results from the primary stage of steel production in EAF. The molten steel tapped from the primary stage then undergoes further refining in a ladle furnace (LF) to remove the impurities. The slag formed at this stage is thus the LF slag [15].

In fact, the total steel output is accompanied by a 15–20% generation of by-product steel slags [16, 17]. The annual production of SFS and BFS in Japan approximates to 11–16 million tonnes and 21–26 million tonnes, respectively [12, 18]. In Europe, 17–21 million tonnes of SFS and 23–29 million tonnes of BFS are generated annually [19]. Meanwhile, China produces more than a hundred million tonnes of SFS [20]. The vast amount of slag, if constantly sent to landfill instead of recycled or treated properly, would stockpile and cause environmental concerns. However, if these by-products can be incorporated as partial substitute of aggregate and cement, twofold environmental benefits can be attained. In addition to the reduction in dumping of slag, decreased dependency on natural resources as the concrete constituent materials can be realized. This is especially beneficial if the incorporation level of these slag by-products can be maximized in the concrete without causing significant performance deterioration. In the past, several attempts have been conducted to investigate the feasibility of using EAF and LF slags as aggregate substitutes in concrete. The EAF and LF slags were explored as partial or full coarse aggregate replacement [21, 22], as well as both fine and coarse aggregate replacements simultaneously [23, 24]. Nevertheless, the comparison of EAF and LF slags has rarely been investigated, while the co-utilization of EAF or LF slag in the presence of GGBS as cement replacement has not been explored before.

Thus, this chapter presents the research works undertaken to provide essential insights into the relevant properties of the sustainable concrete incorporated with locally available EAF and LF slags as 40% aggregate substitute alongside GGBS as 25% cement replacement. In this chapter, the properties of concrete such as workability, compressive strength, water absorption, surface resistivity and mass changes are given attention. Since there is limited study on the use of locally available LF slag in concrete, the use of LF slag as partial fine and coarse aggregate replacement is also compared in this chapter to gain better understanding of this by-product.

3.2 Experimental Details

3.2.1 Binder Materials

Ordinary Portland cement (OPC) CEM I 52.5 N was obtained from a local cement manufacturer for use in this investigation. The GGBS utilized in this research conforms to MS EN 15167-1: 2010 and was obtained from a local slag cement manufacturer. The major chemical composition and loss on ignition (LOI) for OPC and GGBS are given in Table 3.1.

3.2.2 Coarse and Fine Aggregates

For the coarse aggregates, the natural aggregate used was crushed granite whereas the slag aggregates, namely, EAF slag and LF slag, were used as 40% replacement of the crushed granite. The crushed granites and slag aggregates that were used in this study had size range of 10–20 mm. For the fine aggregates, the mining sand was mainly used while fine LF slag was used as 40% replacement. Both mining sand and fine LF slag had maximum size of 5 mm. The physical properties of all coarse and fine aggregates are summarized in Table 3.2, and the particle size distribution is given in Fig. 3.1. The slags are obtained from a local steelmaking plant, and the appearance of the slags is given in Fig. 3.2. The chemical compositions of EAF slag (provided by supplier) and LF slag (range reported in the literature) are listed in Table 3.3.

Table 3.1 Major chemical composition of OPC and GGBS

Binder	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	K_2O	LOI
OPC	64.8	18.7	4.5	3.3	4.1	3.0	0.1	0.7	2.9
GGBS	43.3	34.6	11.9	5.2	0.4	1.9	0.45	0.4	1.6

Table 3.2 Physical properties of aggregates

Material	Granite	EAF slag	LF slag	Mining sand	Fine LF slag
Compacted bulk density (kg/m^3)	1480	1821	1813	–	–
Loose bulk density (kg/m^3)	1427	1708	1696	–	–
Specific gravity	2.64	3.46	2.75	2.59	2.57
Water absorption (%)	0.21	1.29	5.66	1.43	15.07
Fineness modulus	7.79	7.52	7.29	2.84	2.89

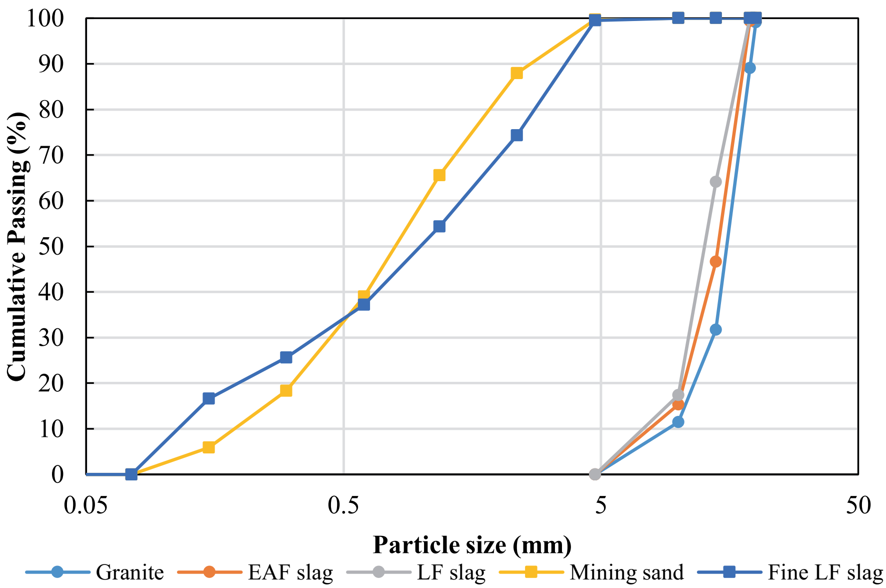

Fig. 3.1 Particle size distribution of aggregates

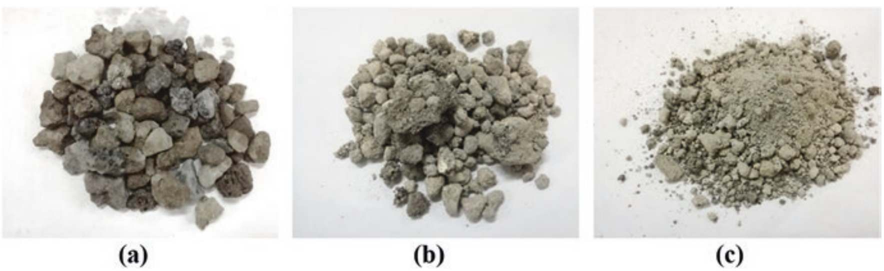

Fig. 3.2 Physical appearance of (**a**) EAF slag, (**b**) LF slag and (**c**) fine LF slag

Table 3.3 Major chemical composition of steel slags

Material	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	MnO
EAF	20.1	12.0	54.6	5.5	6.3	1.6	1.5
LF[a]	30.8–57.0	6.5–32.4	0.1–8.7	1.4–6.6	2.8–9.6	0.0–2.3	0.0–1.0

[a]Retrieved from [25–28]

Table 3.4 Mixture proportions

	Material content (kg/m^3)							
Mix designation	OPC	GGBS	Sand	Fine LF slag	Granite	LF slag	EAF slag	Water
Control	402	–	709	–	1109	–	–	205
EC40G0	402	–	709	–	665	–	581	205
EC40G25	301	101	709	–	665	–	581	205
LC40G0	402	–	709	–	665	462	–	205
LC40G25	301	101	709	–	665	462	–	205
LF40G0	402	–	426	282	1109	–	–	205
LF40G25	301	101	426	282	1109	–	–	205

3.2.3 Mixture Proportion and Specimen Preparation

A total of seven concrete mixtures were prepared according to Table 3.4. The variables in this study include the 40% coarse aggregate replacement (by volume) with EAF slag and LF slag, 40% fine aggregate replacement (by volume) with fine LF slag and the use of GGBS as 25% cement replacement (by mass). Water correction was carried out to account for the water absorption of aggregates.

The mixing of materials was carried out in a rotary drum mixer in the order of coarse and fine aggregates, followed by binder materials and lastly water. A standard mixing procedure was adopted for all mixes. The mixing was done at laboratory condition with a temperature of 29 ± 3 °C and humidity of 75 ± 5%. Upon completion of mixing, the fresh concrete mixture was subjected to slump test, followed by pouring the fresh concrete mixture into steel moulds, compacted on a vibration table and left to set for a day. The concrete specimens were demoulded after 24 h and then cured in laboratory water tank at temperature of 27 ± 3 °C for 28 days.

3.2.4 Test Methods

The workability of fresh concrete mixture is evaluated by conducting the slump test according to BS EN 12350-2: 2009. The slump test was carried out upon completion of the concrete mixing.

After curing of hardened concrete has reached 28 days, 100 mm concrete cube specimens were dried to saturated surface-dry condition and weighed to obtain the density. Then, the cube specimens were subjected to compressive strength test according to BS EN 12390-3: 2009. Three specimens were tested for each mixture, and the average of three compressive strength values was calculated.

Water absorption test in accordance with ASTM C1757-13 was carried out to indicate the porosity of the concrete mixtures. For this test, 75 mm cube specimens which have been cured for 28 days were used. The average of three calculated water absorption values was computed.

Surface resistivity test was carried out using a four-probe Wenner array instrument, which measures the electrical resistance of the concrete [29]. The surface resistivity can indicate the potential corrosion risk of the concrete due to chloride ion penetration. The test was carried out on cylindrical specimens with 100 mm diameter and 200 mm height, and the surface resistivity was measured at the concrete age of 28 days.

The mass changes of concrete specimens upon accelerated ageing and sulphate exposure were also determined to assess the resistance of the concrete towards expansion due to free lime and sulphate attack, respectively. In the accelerated ageing test, after the concrete mixture has been cured for 28 days, 75 mm cube specimens were immersed in 70 °C water for a further 32 days, followed by exposure to laboratory environment for another 90 days. The change in mass of the cured specimens at the end of the test was recorded. For the sulphate attack test, the 28-day cured 100 mm cube specimens were immersed in sodium sulphate (Na_2SO_4) solution with 5% (wt.%) concentration up until 90 days, and the difference in mass was recorded. The Na_2SO_4 solution was changed at monthly interval.

3.3 Results and Discussion

3.3.1 Workability

The slump values of the concrete mixtures are presented in Fig. 3.3. When the granite was substituted with 40% EAF slag or LF slag, the workability of the concrete was reduced. The reduction in slump was about 19% and 44%, respectively. A likely explanation of the reduced workability of the concrete containing the EAF slag is the rough, porous surface and angular particles, which was similarly reported in other researchers [30, 31]. The use of LF slag caused greater reduction in the workability of concrete compared to EAF slag due to the more porous surface of the aggregate, as well as the finer particle size compared to EAF slag. The finer particle size of LF slag (see Fig. 3.1) necessitates higher amount of water required for the larger surface area. When the fine LF slag was used as partial fine aggregate replacement, the adverse effect on the workability was greater compared to the replacement of coarse aggregate with the coarser LF slag at the same replacement level. As much as 62.5% reduction in the slump of concrete was observed compared to the control, this may be attributed to the high water absorption of the fine LF slag, which cannot

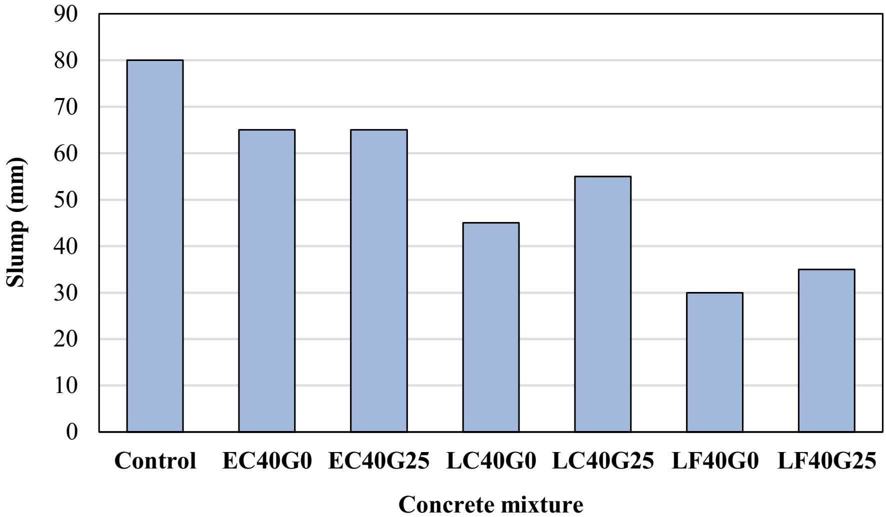

Fig. 3.3 Slump values of concrete mixtures

be effectively compensated through the water correction in the mix design. Rodriguez et al. [32] also reported an increased water demand by 11% when replacing 25% sand with LF slag. In terms of the effect of using 25% GGBS as cement replacement, while it did not affect the slump of concrete with EAF slag, it improved the workability of concrete with LF slag (as coarse and fine aggregate replacement). The improvement in workability when using GGBS is typically ascribed to the morphological characteristics, where the smooth particle surface reduced the requirement. Furthermore, partial replacement of cement with the GGBS increases the paste volume to coat the aggregates, and this is especially useful in concrete with LF slag where the slag has more porous surface and larger surface area.

3.3.2 Density and Compressive Strength

The density and compressive strength of the concrete mixtures at the age of 28 days are presented in Fig. 3.4. Due to the higher specific gravity of EAF slag than granite, the density of the EAF concrete (EC40G0 and EC40G25) was about 2520 kg/m^3, representing an increase of about 6% compared to the control normal concrete. The higher density of EAF slag concrete can be beneficial for application where concrete weight is needed, such as foundation, breakwater block, shoring walls and more [1]. On the other hand, the inclusion of LF slag as partial aggregate replacement had only minor influence on the density of concrete, due to the similar specific gravity of the LF slags as the granite and mining sand. In addition, insignificant effect on the density of the concretes was found with the inclusion of GGBS as 25%

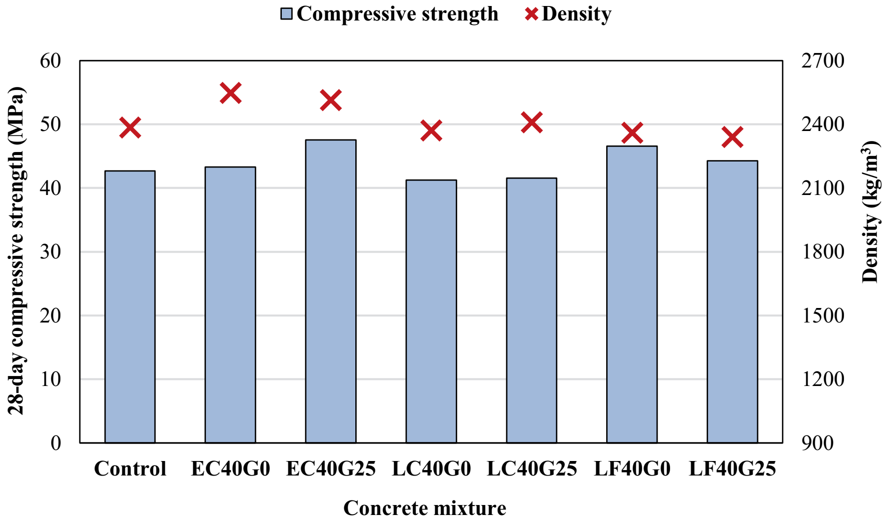

Fig. 3.4 Density and compressive strength of concrete mixtures

partial cement replacement. This could be attributed to the low amount of GGBS incorporated as cement replacement in addition to the comparable specific gravity as cement.

In terms of compressive strength, at the age of 28 days, the EAF slag concrete without GGBS (EC40G0) achieved marginally higher strength than the control normal concrete. This improvement was also reported in previous research work [23]. It is possible that the rough surface texture of the EAF slag can offer stronger bond with the cement matrix, resulting in strength improvement. The intrinsic hardness and angularity of EAF slag could also contribute to the strength increase [33]. The inclusion of GGBS as partial cement replacement in the EAF slag concrete exhibited further improvement on the compressive strength by about 10% due to the matrix densification as a result of the pozzolanic and hydraulic reactions contributed by the GGBS [34]. Although EC40G25 concrete mixture had slightly lower density than the EC40G0 concrete, it had higher compressive strength. This could be attributed to the densified cement matrix when 25% GGBS was present in the mixture. On the other hand, when LF slag was incorporated as partial coarse aggregate replacement, the compressive strength was slightly reduced, likely due to the porous and weaker aggregate structure of the LF slag which can be easily fragmented compared to the granite or EAF slag. However, when fine LF slag was adopted to partially replace fine aggregate, the compressive strength was improved by up to 9% compared to the control normal concrete. There could be three reasons for this: (i) the water correction adopted may not effectively compensate the high water absorption of fine LF slag, resulting in absorption of part of the mixing water and hence reducing the free water/binder ratio; (ii) the fine LF slag contains higher fine content (<0.15 mm) compared to sand, which may improve the granulometry and packing in the concrete [32]; and (iii) there is potential hydraulic activity of the fine particles of LF slag [25].

3.3.3 Water Absorption and Surface Resistivity

The water absorption recorded for the control, EC40G0, EC40G25, LC40G0, LC40G25, LF40G0 and LF40G25, was 1.40%, 1.00%, 1.07%, 1.16%, 1.36%, 1.75% and 1.86%, respectively. The results showed that inclusion of the EAF slag and LF slag as partial coarse aggregate replacement could reduce the water absorption of concrete. This could be attributed to the improved interface bonding between the slag aggregates and cement matrix [35], since the aggregate-matrix interface plays an important role in influencing the durability of concrete. Similarly, Roslan et al. [36] revealed that the packing effect contributed by EAF slag effectively reduced the porosity and occupied the spaces to provide a more dense concrete mixture. On the other hand, an increase in water absorption was observed for the concretes with fine LF slag as fine aggregate replacement, as the fine LF slag has high water absorption and porosity compared to sand. The influence of GGBS, however, is only minimal on the water absorption of the produced concretes.

The surface resistivity of concretes obtained based on the Wenner four-probe method is given in Fig. 3.5. According to the classification in AASHTO T358-19, surface resistivity of less than 12 kΩ-cm may indicate high chloride ion penetrability, whereas surface resistivity between 12 and 21 kΩ-cm indicates moderate chloride ion penetrability while surface resistivity above 21 kΩ-cm indicates low chloride ion penetrability. According to the results obtained, the control normal concrete had surface resistivity of about 13 kΩ-cm and moderate chloride ion resistance. The surface resistivity of the concrete was increased in the presence of EAF slag, possibly due to the improved aggregate-matrix interface and ferrite oxide content, resulting in enhanced durability [15]. Further increase in the surface resistivity was found with the inclusion of GGBS in the EAF slag concrete due to matrix densification. However, in the case of LF slag partially replacing coarse aggregate, the concrete experienced high chloride ion penetrability as the surface resistivity recorded was below 12 kΩ-cm. This could be attributed to the porous nature of the LF slag itself, which can increase permeability of the concrete [29]. Similarly, the concrete containing fine LF slag as partial fine aggregate replacement recorded surface resistivity around the borderline of ‘moderate’ and ‘high’ chloride ion penetrability. Therefore, based on the findings of the surface resistivity, it is apparent that the choice of EAF slag is more suitable compared to LF slag as partial aggregate replacement in concrete; in addition, the beneficial effect of GGBS is more apparent in the EAF slag concrete.

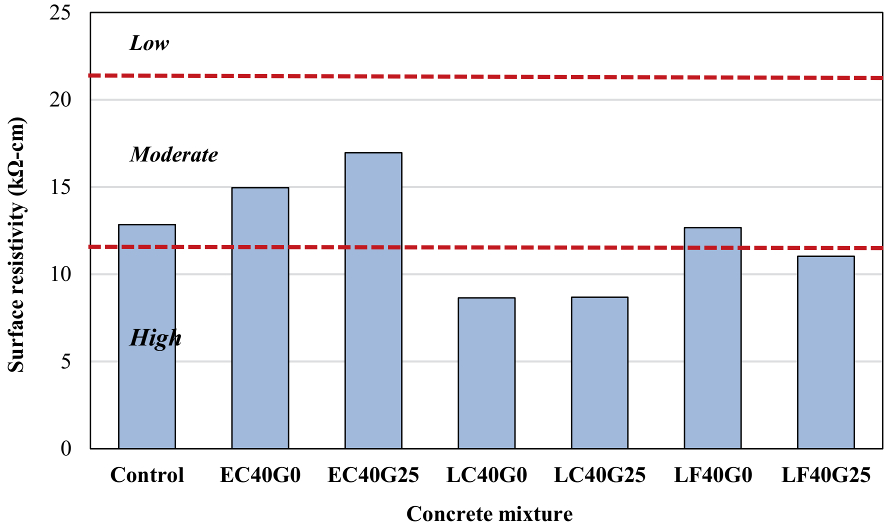

Fig. 3.5 Surface resistivity of concrete mixtures

Table 3.5 Compressive strength and mass changes after a 90-day exposure to sulphate solution

Mix designation	Mass change due to accelerated ageing (%)	Mass change due to immersion in Na_2SO_4 (%)
Control	−2.55	0.18
EC40G0	−2.40	0.09
EC40G25	−2.26	0.07
LC40G0	−3.39	0.08
LC40G25	−3.22	0.06
LF40G0	−3.74	0.22
LF40G25	−3.28	0.15

3.3.4 Mass Change

The mass changes of the concrete mixtures due to accelerated ageing and Na_2SO_4 exposure are presented in Table 3.5. The use of slag aggregates is often associated with concerns over expansion of the resulting concrete due to the presence of free lime and magnesia; hence, the mass change of the concrete after accelerated ageing was assessed. When substantial expansion has occurred, the internal stress generated could weaken the concrete and cause mass loss [37]. Generally, the concretes containing LF slags (as partial coarse or fine aggregate replacement) experienced higher mass loss compared to the control normal concrete as well as the concretes containing EAF slag. It should be noted that prior to usage in the concrete, the LF slags have already been exposed to natural weathering over a substantial period; therefore, the mass loss could be much greater in actual.

In terms of the observation of mass change when exposed to Na_2SO_4, in the short observation duration, the concrete specimens experienced gain in mass due to the formation of expansion products. The higher mass gain therefore may indicate increased susceptibility towards reaction with the penetrating external sulphate ions. The concretes with EAF and LF slags as partial coarse aggregate replacement generally had lower mass gain than the control normal concrete, whereas the concretes with fine LF slag had notably higher mass gain. This suggests possibility of weaker sulphate resistance of the latter due to the high porosity of the fine LF slag and subsequently the produced concrete. Longer exposure duration is however recommended to monitor the sulphate resistance of the concretes and draw better conclusions. In overall, in view of the mass change observations in assessing the resistance to expansion and Na_2SO_4 exposure, it can be said that the concrete mixture containing 40% EAF slag as coarse aggregate replacement and 25% GGBS as cement replacement performed the best.

3.4 Conclusion

This study investigates the use of EAF slag (as 40% coarse aggregate replacement), LF slag (as 40% coarse aggregate replacement) and fine LF slag (as 40% fine aggregate replacement) in a sustainable concrete which also incorporated 25% GGBS as partial cement replacement. Based on the obtained results, it is concluded that, among the slags used as partial aggregate replacement, EAF slag as 40% coarse aggregate replacement gave the best performance of concrete. The reduction in workability was the least, while improvements were found in terms of increased compressive strength and surface resistivity, lowered water absorption as well as mass changes due to accelerated ageing and sulphate exposure. These improvements in the EAF slag concrete were also further enhanced with the use of 25% GGBS as partial cement replacement, hence potentially allowing higher usage of by-products from the steel industry to produce a more sustainable concrete.

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