Effect of Steel Slag As Fine and Coarse Aggregate on Pore Structure and Freeze-thaw Resistance of High-strength Concrete

Raed M. Abendeh [1)]****, Rana A.M. Alhorani*** [1)]***, Hesham S. Ahmad*** [1)] ***and Mousa I. Bani Baker*** [1)]

[1)] Department of Civil and Infrastructure Engineering, Al-Zaytoonah University of Jordan, Amman, Jordan.
* r.abendeh@zuj.edu.jo; raed100@yahoo.com

ABSTRACT

Steel slag usage in concrete can be a promising and sustainable approach to reduce natural resources shortages, landfill costs and potential pollution. In this work, the behavior of concrete prepared with varying replacements of recycled Steel Slag Aggregate (SSA) of natural aggregate ranging from 0% to 75% was investigated. Concrete behavior was evaluated using different tests; namely, compressive and flexural strengths, mass loss, water absorption, permeability and freezing/thawing (F/T) effect. The incorporation of SSA into concrete improved the strength and durability of mixtures prepared with high replacement ratios of SSA. The compressive strength was increased at about 12% for the 75% replacement ratio of fine aggregate compared to the control specimens, while concrete containing SSA as coarse aggregate showed the highest compressive strength at about 49.2 MPa. The flexural strength of the present mixtures was increased by about 13% and 15% for concrete with substitutions of 75% SSA of fine and coarse aggregate, respectively. The replacement of SSA for natural coarse aggregate at 75% was fundamental in enhancing the resistance to F/T noticeably as indicated by ultrasonic pulse velocity measurements.

KEYWORDS: Steel slag aggregate, Compressive strength, Flexural strength, Concrete permeability, Freeze-thaw action, Ultrasound pulse velocity.

INTRODUCTION

Steel by-products exist in the form of steel slag, steel sludge and other forms. The manufacture of each ton of steel makes up to four tons of waste (Das et al., 2007). In iron ore and crude steel processing, impurities and slag combine to form iron and steel (ferrous) slag for a ready market in the construction industry (Muhmood et al., 2009; Yildirim and Prezi, 2011; Mineral Commodity Summaries, 2021). Approximately 116 million tons of steel slag are produced annually in China (Guo et al., 2018a) and the United States (National Mineral Information Center, 2019). In Jordan, the amount of iron slag waste generated daily is about 20 tons (Abendeh and Bani Baker, 2020).

Steel slag aggregate are categorized according to the furnace as: Blast Furnace Slag (BFS), Ladle Furnace Slag (LFS), Basic Oxygen Furnace Slag (BOFS) and Electric Arc Furnace Slag (EAFS). The steel slag's physical and chemical properties are affected by raw steel processing and slag cooling rate (Chandru et al., 2020).

The search for suitable applications to reduce the huge amount of industrial steel waste is essential to protect the environment by recycling waste. One such application is the use of waste steel to partially replace fine aggregate, coarse aggregate or cementitious materials' production. The increasing usage of industrial steel waste in the construction industry requires a high level of knowledge of its impact on concrete's performance and durability in different environmental conditions (Qasrawi, 2018; Qasrawi, 2020; Shaiksha et al., 2020; Srinivas et al., 2021; Abd El-Hakim et al., 2021; Bian et al., 2021).

The mineral contents of steel slag include amorphous silicon dioxide, calcium oxide, tricalcium silicate, dicalcium silicate and tetracalcium

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aluminoferrite (Chen et al., 2020). Motz and Geiseler (2001) and others concluded that the active natural hydration components of steel slag allow the use of fine ground steel slag as a mineral additive for cement and concrete. The angular shape and abrasion resistance of coarse steel slag aggregate (SSA) as substitution to natural aggregate in mixtures enhance the wear resistance and roughness of concrete. However, the volumetric expansion of steel slag resulting from the reaction of amorphous oxides on the surfaces of slag particles is the primary determinant of its use in concrete mixtures (Wang et al., 2020; Chandru et al., 2020; Pellegrino and Gaddo, 2009; Wang and Yan, 2010; Jiang et al., 2018).

Arivalagan (2014) examined the mechanical properties and durability of concrete (at 7 days and 28 days) made of ground granulated blast furnace slag (GGBFS) with 20, 30 and 40% replacing cement by weight. It was revealed that 20% GGBFS substitution for cement increased the compressive strength of concrete at 28 days, lowered heat of hydration and showed better workability and chemical attack resistance. Guo et al. (2018b) conducted compression and split tests on concrete containing steel slag sand to verify the monotonic and impact behaviors of the mixtures. They found that substituting steel slag for 20% of fine aggregate can enhance the static and dynamic compressive strength of specimens. However, they also noted that the surface roughness of the steel slag leads to insufficient cement hydration due to the increased water absorption of the slag. Thus, high proportions of steel slag to replace fine aggregate negatively affected the mechanical properties of concrete (compressive strength, modulus of elasticity and Poisson's ratio). Guo et al. (2019) used Basic Oxygen Furnace Slag (BOFS) aggregate for fine natural aggregate in ordinary concrete and High-strength Concrete (HSC). The study results showed that the incorporation of BOFS to replace the fine aggregate improved the compressive strength by 14% and 5% for normal concrete and HPC, respectively. The incorporation of BOFS had a slight effect on the concrete modulus of elasticity and the highest toughness was obtained at 80% and 30% BOFS for normal concrete and HSCs respectively. Hydration of C_2S and C_3S content in BOFS aggregate and their surface roughness enhanced the concrete's mechanical properties.

The effect of BOFS coarse aggregate replacement with volume ratios of 0, 50 and 100% on the performance of Activated Alkali Slag Concrete (AASC) and Activated Alkali Fly Ash Concrete (AASFC) was also compared with that of ordinary Portland cement concrete by Palankar et al. (2016). The compressive strength of AASC and AASFC containing coarse steel slag aggregate decreased by 6% and 14% for 50% and 100% replacement ratios respectively, compared to that of normal concrete. The calcite formation on the slag surface impairs the bonding between the cementitious material and aggregate; however, the compressive strength of all concrete mixtures ranged between 55 ± 5 MPa at 28 days. In contrast, the incorporation of BOFS caused an increase in water absorption, permeable pore size and strength loss in concrete mixtures when they were exposed to sulfuric acid and magnesium sulphate attack.

Several studies have observed the effect of using steel slag with other waste materials on the concrete's mechanical properties. Chunlin et al. (2011) prepared four concrete mixes keeping all design parameters constant except for the aggregate compositions: crushed limestone/quartz sand, steel slag (SS) for fine and coarse aggregate, limestone/quartz sand plus 10% crumb rubber powder and SS for fine and coarse aggregate plus 10% crumb rubber powder. The experiments showed that the compressive strength of concrete containing steel slag was sufficient, while the flexural strength was slightly lower than that of conventional concrete. The researchers concluded that the shrinkage and expansion of concrete were reduced to some extent because of the expansion of steel slag. The replacement of fine steel slag with scrap tire particles produced sufficient strength and volume stability of concrete and its strength characteristics were equivalent to those of conventional concrete.

Also, the fire resistance and mechanical properties of concrete containing steel slag and waste glass were investigated by Yu et al. (2016). It was found that the inclusion of electric arc furnace slag (EAFS) as well as glass waste improved the concrete's workability and mechanical properties. Furthermore, the inclusion of EAFS porous aggregate reduced the rate of heat transfer within the concrete by reducing heat generation within the concrete compared to the natural aggregate.

Saxena and Tembhurkar (2018) studied wastewater and steel slag (15–100%) influence on concrete properties. The 50% replacement of natural aggregate by steel slag aggregate exhibited a 33% increase in compressive strength, 9.8% in flexural strength and 22% in elasticity modulus of concrete. The dense microstructure of concrete and its durability were verified by conducting ultrasound pulse velocity tests, SEM analysis and rapid chloride permeability tests. The EAFS's porous nature enhanced the cement matrix interface with aggregate and thus resulted in higher mechanical performance. The concrete incorporating steel slag aggregate revealed higher ultrasound pulse velocities and lower chloride ion penetrations (40-70%) in comparison to control mixtures.

Biskri et al. (2017) prepared High-performance Concrete (HPC) by mixing granulated blast furnace slag, silica fume and incorporating of steel slag or crystallized steel slag for coarse limestone aggregate. The results revealed that the inclusion of steel slag aggregate in concrete mixtures enhanced their mechanical properties, as the compressive strength of HPC with steel slag and crystallized steel slag increased by 34% and 21%, respectively, compared to HPC prepared with limestone aggregate. Also, the rupture modulus of HPC increased by up to 35% and 18% when steel slag and crystallized steel slag replaced the limestone aggregate. The incorporation of crystallized steel slag and steel slag slightly heightened water porosity by 10.3% and 11.9%, respectively, compared to 7.7% for HPC with limestone aggregate. The same trend was observed for the gas permeability of HPC containing the same aggregate, but moderate permeability to chlorine ions was detected due to the granular porosity of the steel slag aggregate.

The limitations of steel slag usage to replace Portland cement and natural aggregate due to the volume instability were investigated by Mo et al. (2017). Blending mixtures were prepared by replacing natural aggregate with steel slag and adding 60% calcium-free slag powders, 20% Portland cement, 20% magnesia and reactive lime. The concrete mixtures were treated with carbonate at a concentration of 99.9% CO_2. The findings showed that substituting limestone and sand aggregate by steel slag aggregate enhanced the compressive strength of the treated concrete by up to five times the conventional concrete's strength as a result of the enhancement of the transition zone between the steel slag particles and the cement matrix. In addition, concrete previously treated with carbon dioxide showed lower expansion than concrete previously cured in 60 °C water in an accelerated manner. Mo et al. (2020) produced artificial steel slag by mixing Portland cement, fly ash and steel slag powder in a carbon dioxide treatment process. Then, they investigated the influence of carbonated artificial steel slag aggregate on concrete performance. The concrete with a compressive strength of 45.5 MPa and constant volume was developed and the formation of calcium carbonate as aggregate binder resulted in dense microstructures and low cracking values.

Therefore, incorporating steel slag into concrete mixes for the construction industry is promising and addresses environmental degradation by recycling steel waste instead of consuming natural aggregate. Although many studies have focused on the inclusion of SSA in concrete mixtures for partial replacement of natural aggregate or cement, few studies have examined the durability of SSA-containing concrete. Concrete is usually subjected to stringent environmental conditions, such as freeze-thaw action. Literature studies have shown that freezing and thawing cause peeling of the concrete surface, internal cracks and severe damage to concrete pavements of highways, bridges and other structures. The objectives of this work are to verify the strength and durability of SSA-containing concrete as follows: (i) to recycle waste steel by partially replacing natural aggregate into concrete mixes and demonstrate whether this can be a good approach for recycling large proportions of waste steel, (ii) to observe SSA influence on the mechanical properties and durability of concrete against freezing and thawing cycles (up to 250 F/T cycles). The experimental work in this study includes testing 63 concrete specimens that were produced by partial replacement of fine or coarse aggregate with 0, 25, 50 and 75% SSA. The mechanical properties of concrete mixtures and their durability were studied by means of compressive strength, flexural strength, mass loss, water absorption and water permeability. Ultrasound pulse velocities of the mixtures were also measured to test their resistance to freezing and thawing.

Experimental Program

Materials

The experimental program section describes material characterization and concrete specimen preparation to verify the effect of steel slag as a fine or coarse aggregate on the pore structure and freezing and thawing resistance of high-strength concrete.

Cement and Natural Aggregate

For the purpose of this study, concrete mixtures of CEM I 52.5 N Portland cement were prepared according to the standard UNE-EN 1 97-1: 2000. The percentages of chemical compounds for the cement used are given in Table 1. Natural crushed limestone aggregate and silica sand were used in concrete mixes. A maximum coarse aggregate size of 19mm was included. The fine aggregate was mixed with silica sand by weight of 60.24% of the concrete mixes. Table 2 illustrates the physical properties of natural aggregate used. The coarse and fine aggregate gradients are displayed in Figure 1.

Table 1. The percentages of chemical compounds for the cement used and steel slag (%)

Compound	Cement	Steel slag aggregate
CaO	62.895	45.1
SiO_2	19.29	12.5
Iron FeO or Fe_2O_3	4.205 (Fe_2O_3)	15.3 (75% FeO, 25% Fe_2O_3)
TiO_2	-	0.2
Al_2O_3	5.07	4.1
P_2O_5	-	0.7
MnO	-	4.8
MgO	2.83	8.9
SO_3	3.085	-
Metallic Fe	-	8.3
Sulfur S	-	<0.1
Na_2O	-	-
K_2O	0.81	-
Free lime	1.655	-

Table 2. The physical properties of natural aggregate used

Aggregate Type	Bulk Specific Gravity	Water Absorption (%)	Fineness Modulus
Coarse	2.5	4.5	5.9
Fine	2.47	7	2.78

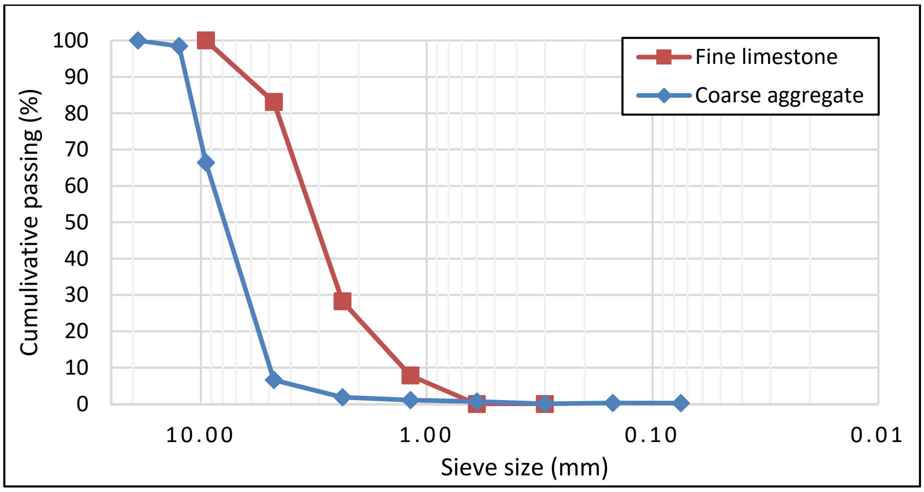


Figure (1): The coarse and fine aggregate gradients

Steel Slag

Available local steel slag aggregate was used to partially replace fine or coarse aggregate in concrete mixes designed in this study. Figure 2 shows specimens of the fine and coarse steel aggregate used. Table 3 presents the physical properties of SSA. The SSA size analysis is shown in Fig. 3. The fineness moduli of 4.41 and 3.16 were found for the coarse and fine steel slag aggregate, respectively. The chemical compositions of the used steel slag were obtained by X-ray fluorescence analysis, as shown in Table 1. As seen, SSA is composed of CaO, SiO_2, Iron FeO or Fe_2O_3, Al_2O_3, MnO, MgO and Metallic Fe.

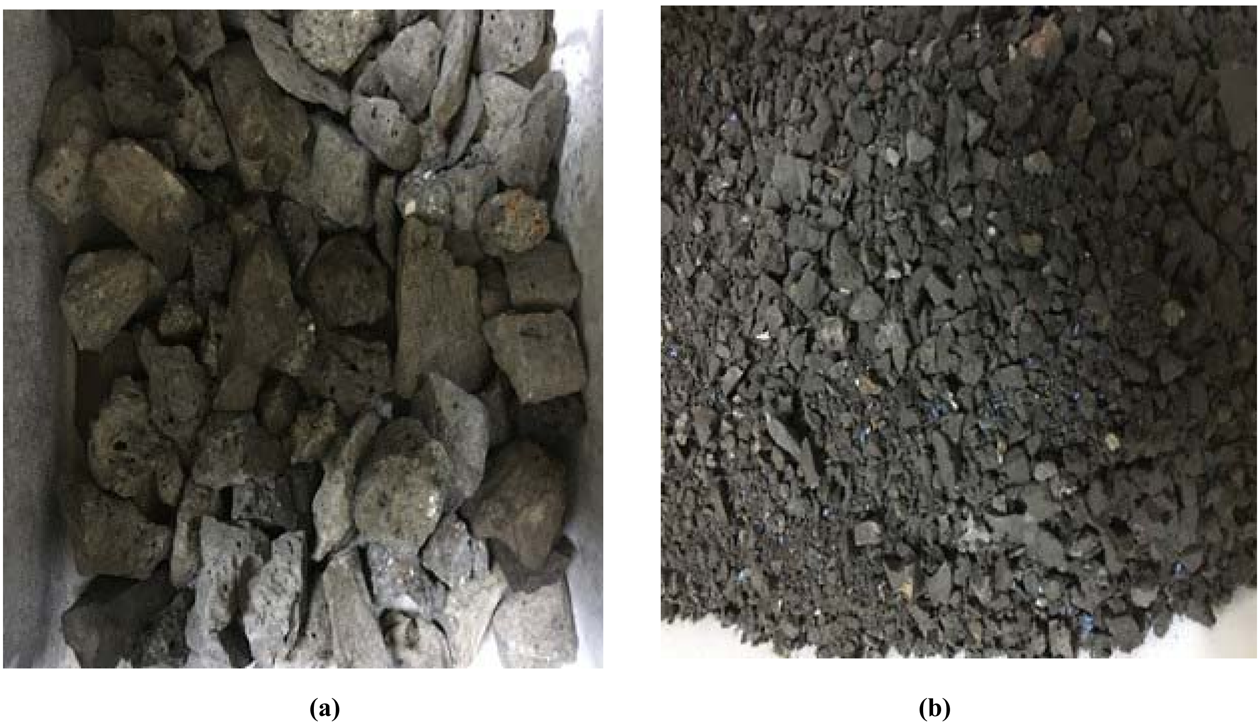


Figure (2): Specimens of steel slag aggregate: (a) Coarse SSA (b) Fine SSA

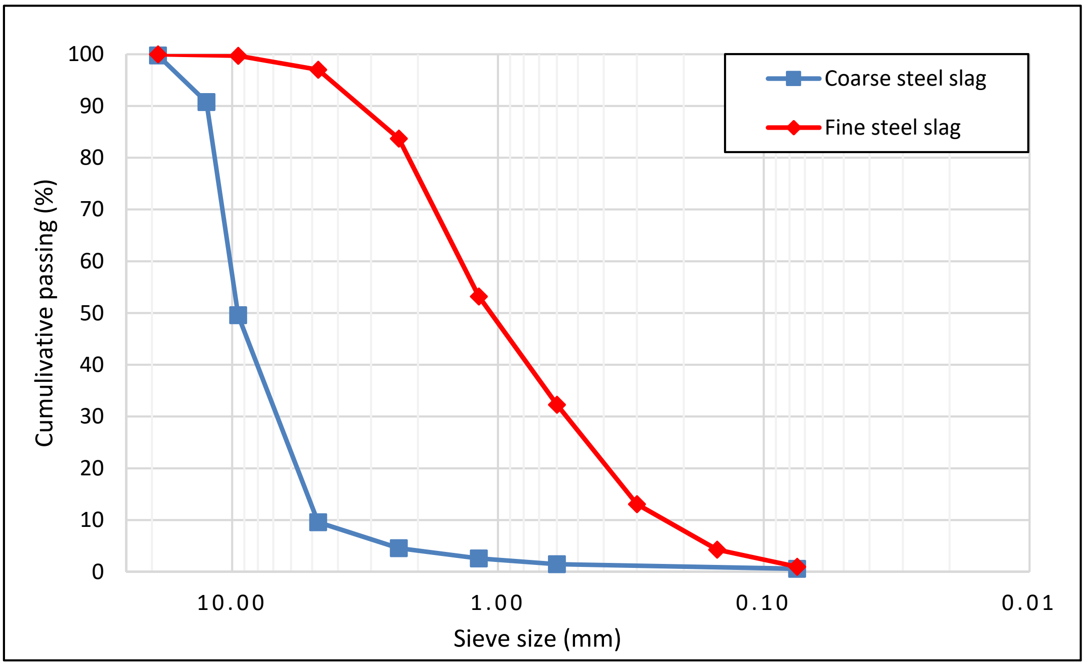


Figure (3): The SSA size analysis

Table 3. The physical properties of SSA

Aggregate Type	Bulk Specific Gravity	Water Absorption (%)	Fineness Modulus	Aggregate Crushing Value (%)	Los Angeles Abrasion (%)
Coarse	3.26	1.7	4.41	19	20.5
Fine	3.22	2.5	3.16		

Design of Concrete Mixtures

Seven types of concrete mixes were designed with partial replacement ratios of SSA for coarse or fine aggregate varying between 0% and 75% (25% increase). The concrete mixtures were prepared with a w/c ratio of 0.5, 1.66 and 3.33 by weight of cement for fine and coarse aggregate. The slump test for controlling the concrete consistency was conducted according to ASTM C143 (ASTM C143/C143M-20 (2020)).

Preparation of Concrete Specimens

The mechanical properties of concrete specimens containing different substitution ratios of SSA (0, 25, 50 and 75%) and their durability to freezing-thawing action were examined in terms of density loss and pulse velocity compared to the control specimens. Following the relevant ASTM standards, a total of 63 specimens were tested for the effect of SSA on the mechanical properties and durability characteristics of concrete, as described below.

Compressive and Flexural Strength Tests

Three cubes of 100 mm size for each mixture were tested for compressive strength at 28 days according to BS 1881 Part 108. The compression tests were carried out using a 2000 kN testing machine at a loading rate of 150 kN/min. Also, three beams of 75 x 75 x 300 mm size were prepared and tested for flexural strength of concrete mixes before exposure to frost action according to ASTM C78 Test Method (ASTM C78/C78M-21 (2021)). All concrete specimens were poured into molds and kept in a curing tank under a moisture condition for 24 hours. After removing the molds, the specimens were placed for 28 days under moisture curing at room temperature. The average of three specimens was taken to obtain the compressive and flexural strength of the mixtures.

Water Absorption and Permeability Tests

The 100 mm and 200 mm blocks were prepared for water absorption and water permeability tests according to ASTM C642 (ASTM C642-97 (1997)) and DIN EN 12350-1: 2009, respectively. The 200-mm cubes were exposed to a 5-bar water pressure for 72 hours in the water permeability test. A total of seven cubes were tested. The specimens were then cut in half to estimate water penetration.

Freeze-Thaw Action Tests

The freeze-thaw action tests were conducted following ASTM C666 (Procedure A) (ASTM C666/C666M-15 (2015)). The effect of steel slag as fine or coarse aggregate on the freezing and thawing resistance of high-strength concrete has been studied. Prisms of 75 x 75 x 300 mm in size were prepared. The concrete prisms were frozen in water at (-16°C) and subsequently thawed for 2.5 hours in one freeze-thaw cycle. The concrete specimens were tested for mass loss and ultrasonic pulse velocity (UPV) before and after exposure to freeze-thaw action up to 250 cycles. The ultrasonic pulse velocities were measured following ASTM C 597 (ASTM C 597-09 (2009)). The mass losses and UPV results were taken after 0, 100, 150, 200 and 250 F/T cycles. The flexural strength test of 14 prisms after exposing to 250 F/T cycles was also performed and the average of two prisms per mixture was considered for strength results.

RESULTS AND DISCUSSION

Slump-flow Test

The slump-flow test results of concrete mixtures with 0, 25, 50 and 75% SSA are shown in Table 4. It was found that concrete slump decreased with the increase of SSA replacement ratios for fine or coarse aggregate, indicating a decrease in the workability of the mixtures. The decrease in slump values occurred due to the super cohesion between steel slag aggregate and cement paste, where the higher reduction rate of slump values of concrete containing SSA for coarse aggregate is attributed to the angular shapes and rough surfaces of coarse steel slag (Yu et al., 2016; Zareei et al., 2019).

Table 4. Slump test results for concrete mixtures incorporating different SSA%

Fine Aggregate		Coarse Aggregate	
SSA content	**Slump, mm**	**SSA content**	**Slump, mm**
0% SSA	70	0% SSA	70
25% SSA-F*	67	25% SSA-C**	66
50% SSA-F	67	50% SSA-C	65
75% SSA-F	65	75% SSA-C	63

* SSA-F indicates SSA replacement for natural fine aggregate.
** SSA-C: indicates SSA replacement for natural coarse aggregate.

Hardening Mechanical Properties of Concrete

Density

Table 5 shows the effect of steel slag as fine or coarse aggregate on the dry density of hardened concrete specimens. The average density increased from 2260 kg/m^3 for control specimens to 2390 kg/m^3 for concrete containing 75% fine SSA, while the dry density increased to 2420 kg/m^3 for concrete containing 75% coarse SSA. The results are consistent with those of Yu et al. (2016). The increase in dry density of SSA-containing concrete can be explained by the larger bulk density values of SSA relative to those of natural aggregate.

Table 5. The density and water absorption of concrete specimens containing SSA%

SSA Content	Density, kg/m^3	Water Absorption, %
0% SSA	2260	2.21
25% SSA-F*	2290	1.997
50% SSA-F	2350	1.87
75% SSA-F	2390	1.68
25% SSA-C**	2330	1.93
50% SSA-C	2380	1.765
75% SSA-C	2420	1.58

* SSA-F indicates SSA replacement for natural fine aggregate.
** SSA-C: indicates SSA replacement for natural coarse aggregate.

Compressive Strength

The compressive strength test results for inclusion of different proportions of SSA in concrete mixes are shown in Table 6. The average compressive strength results of concrete specimens at 28 days are also shown in Figure 4. As we have seen, the partial replacement of fine or coarse natural aggregate with SSA increased the compressive strength of concrete specimens. Compared with the control specimens, the increase in compressive strength of concrete ranged from 8.11% to 20.88% and 4.05% to 12% when incorporating SSA for coarse or fine aggregate, respectively, with the highest compressive strength of 49.2 MPa for 75% coarse SSA. The influence of SSA on the concrete compressive strength can be related to the increase in hydration products from the cementitious composition of steel slag (Mo et al., 2017). Also, the rough surfaces and angular shapes of steel slag aggregate can enhance the mechanical bonding between cement matrix and concrete aggregate.

The effect of steel slag aggregate on the concrete compressive strength has been investigated in previous studies (Arribas et al., 2014; Peng and Hwang, 2010; Kothei and Malathy, 2012). Singh and Siddique (2016) found that the inclusion of steel slag by 10, 25 and 40% as a partial substitute for fine aggregate improved the compressive strength of concrete by 4, 13 and 21% compared to the control mixtures. Qasrawi (2012) also concluded that using steel slag with a relatively high content of Fe_2O_3 as coarse aggregate enhances the compressive and flexural strength of concrete.

Table 6. Strength results for concrete mixtures incorporating different SSA%

SSA content	Compressive Load (N)	Average Compressive Strength (MPa)	Flexural Load (N)	Average Flexural Strength (MPa)
0% SSA (Control)	410	40.7	4.88	4.63
	417		4.6	
	400		4.4	
25% SSA-F*	429	42.35	5.1	4.9
	431		4.87	
	417		4.72	
50% SSA-F	452	43.9	4.95	5.0
	437		4.93	
	429		5.2	
75% SSA-F	455	45.57	5.4	5.23
	463		5.1	
	449		5.2	
25% SSA-C**	440	44	5.21	5.0
	451		5.0	
	431		4.8	
50% SSA-C	442	45.5	5.36	5.3
	456		5.19	
	468		5.41	
75% SSA-C	488	49.2	5.30	5.34
	518		5.41	
	470		5.30	

* SSA-F indicates SSA replacement for natural fine aggregate.

** SSA-C: indicates SSA replacement for natural coarse aggregate.

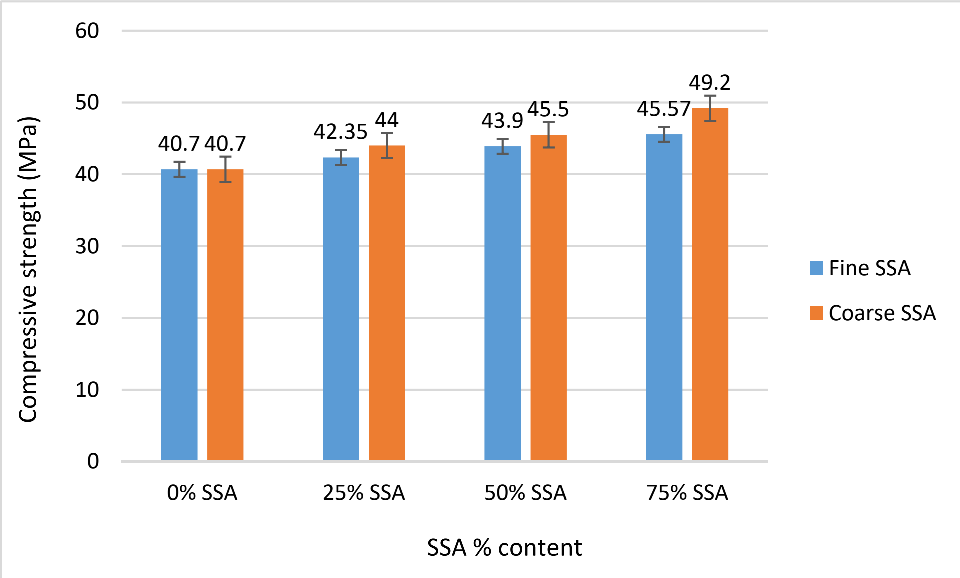


Figure (4): Average compressive strength results for concrete mixtures incorporating different SSA%

Flexural Strength

Table 6 and Figure 5 show the flexural strength results for concrete specimens containing different SSA ratios to partially substitute coarse or fine aggregate. The influence of SSA on the flexural strength of concrete was similar to that found when testing the compressive strength of mixtures. The incorporation of SSA had a positive effect on the flexural strength of all concrete mixtures. The increase in the flexural strength of the SSA-containing concrete specimens compared to the control specimens may indicate a hardening of the intermediate transfer zone between the cement matrix and the aggregate (Nikbin et al., 2014). The test results also showed that the flexural strength of the mixtures increased with the increase of SSA ratios and the highest increase in flexural strength of concrete was about 15.33% for incorporating 75% SSA for coarse aggregate, while the increase in flexural strength was about 12.9% when 75% SSA replaced fine aggregate in the mixtures.

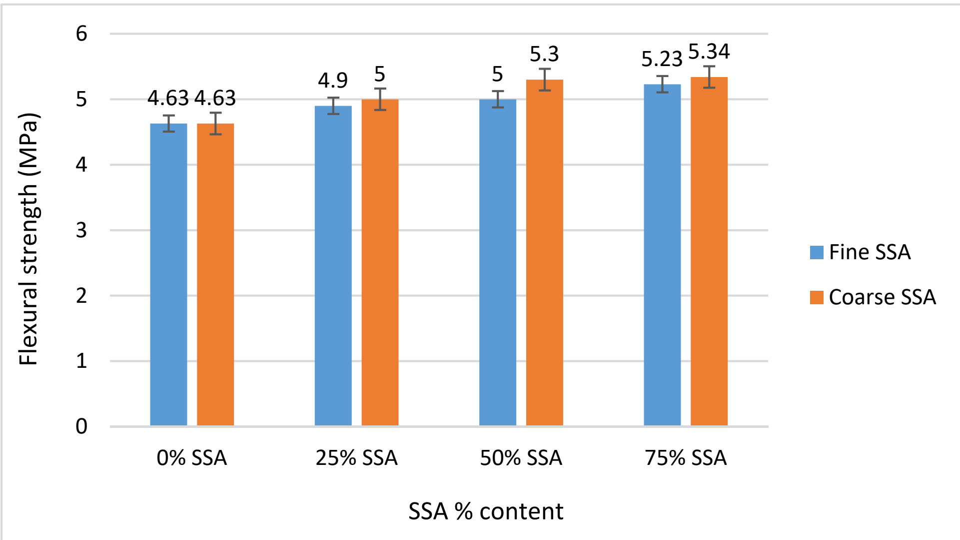


Figure (5): Average flexural strength results for concrete mixtures incorporating different SSA%

Water Absorption

The influence of using SSA to replace fine or coarse aggregate in concrete mixtures on the 28-day water absorption is shown in Figure 6. It was observed that the water absorption of the concrete specimens decreased with the increase of the SSA ratios. Moreover, the fine SSA-containing concrete specimens showed greater water absorption compared to the coarse SSA-containing concrete specimens, which may be due to the relatively higher water absorption value of fine steel slag than that for the coarse steel slag shown in Table 3. As seen in Table 5, concrete containing 75% SSA to replace coarse or fine aggregate recorded water absorption equal to 1.58% and 1.68%, respectively, compared to 2.21% for control specimens. These results about the effect of using SSA on the water absorption property could confirm the compact microstructure of the produced concrete as well as the effect of low SSA absorption. In previous research, Singh and Siddique (2016) found that partial replacement of fine aggregate with steel slag in concrete mixtures reduced water absorption in all concrete mixtures, with iron slag replacing 40% of fine aggregate showing water absorption of 4% instead of 4.8% for control mixtures.

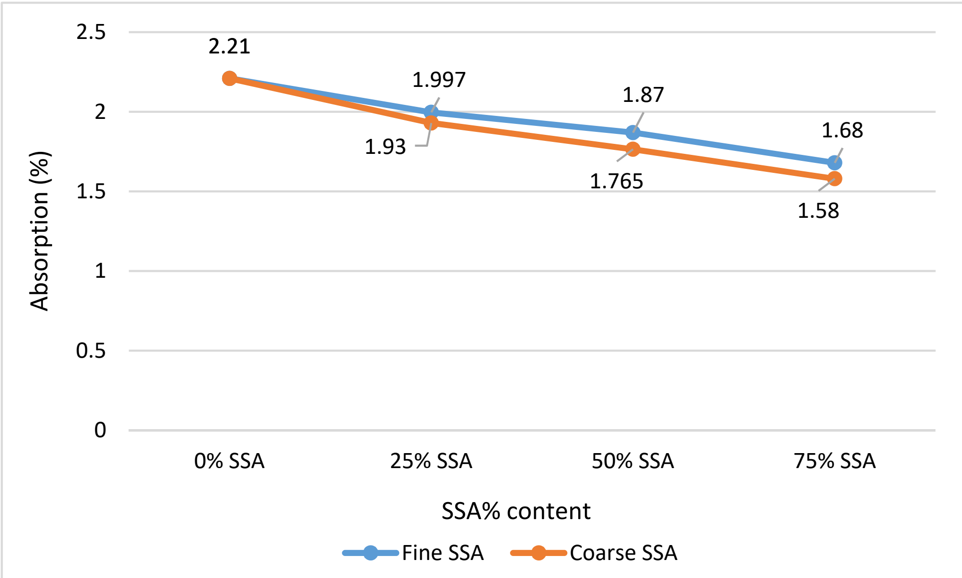


Figure (6): Water absorption results for concrete mixtures incorporating different SSA%

Water Permeability

Table 7 provides water penetration depth measurements for concrete specimens containing SSA for fine or coarse aggregate. The permeability results showed that increasing the content of SSA in concrete mixtures leads to a significant decrease in the water penetration depth compared to normal concrete. The control specimens recorded a water penetration depth of 75 mm while this depth decreased to 46 mm and 45 mm for mixed concrete with 75% SSA for fine or coarse aggregate, respectively. The inclusion of SSA substitutes in concrete mixes reduces the porosity and permeability of hardened concrete. This confirms the previously observed improvement in compressive strength associated with low permeability and a dense microstructure where water permeability is more related to pore type and size rather than total porosity (Tsivilis et al., 2003). The decrease in water permeability can be explained by the improvement of the cement paste microstructure by filling the porous structure with steel slag hydration products that reduce contact and pore accessibility (Sonebi and Nanukuttan, 2009).

The depth of water penetration in hardened concrete is measured to assess the porosity and potential durability of concrete against an aggressive environment. Concrete with values less than 50 mm obtained under a water pressure of 5 bar for 72 hours, is considered impermeable, while concrete with a water penetration depth of less than 30 mm is considered impermeable and compatible with harsh environmental conditions (Neville, 1995). According to TS EN 12390-8 (TS EN 12390-8 (2002)), the present study shows that concrete containing 75% SSA for fine or coarse aggregate possesses high durability as the water penetration depth was less than 50 mm.

Table 7. Permeability of concrete mixtures made with different SSA percentages

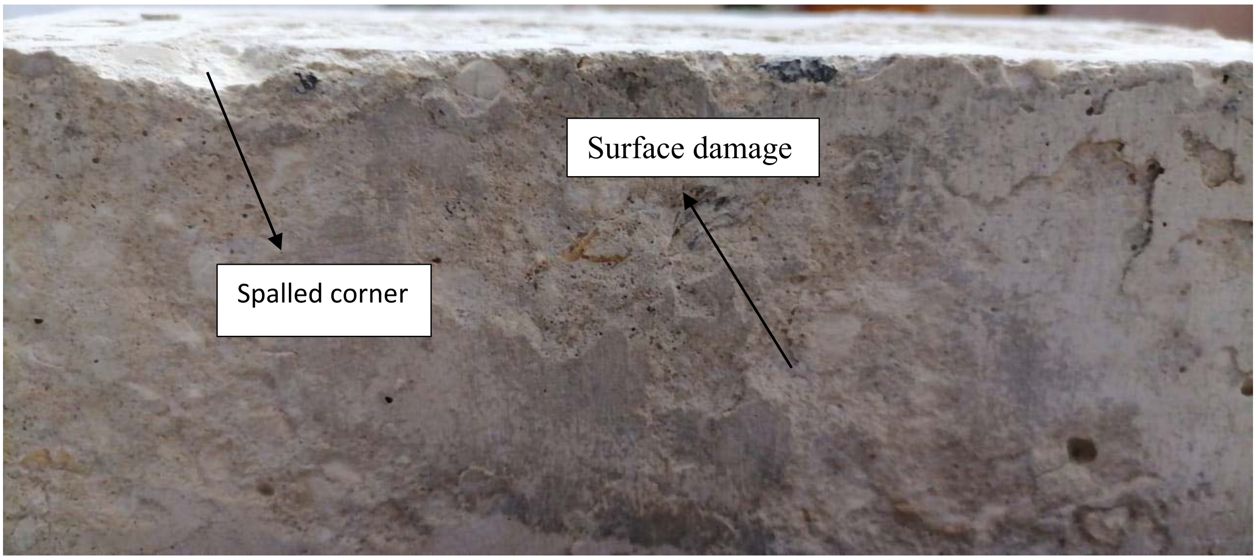
Mixture Type	Permeability (mm)
0% SSA (Control)	75
25% SSA-F	71
50% SSA-F	53
75% SSA-F	46
25% SSA-C	69
50% SSA-C	50
75% SSA-C	45

Resistance to Freezing and Thawing

Resistance of concrete specimens to freezing and thawing cycles was examined through measuring loss in mass, compressive and flexural strength and ultrasonic pulse velocity (UPV). Table 8 presents the mass loss results and UPV readings for concrete specimens with different replacement ratios of SSA at 0, 100, 150, 200 and 250 F/T cycles. Figure 7 shows the surface appearance of control concrete and concrete containing 75% SSA, both after 250 F/T cycles. Several cavities could be observed in the control concrete specimens and as obvious and gradually extending cracks appeared, aggregates were exposed and some corners fractured. On the other hand, concrete specimens containing 75% SSA showed little surface damage.

Table 8. Freeze and thaw test results

Specimen 76x76x 305 mm	Weight (g)	UPV (m/s)	100 F/T cycle		150 F/T cycle		200 F/T cycle		250 F/T cycle	
			Weight (g)	UPV (m/s)	Weight (g)	UPV (m/s)	Weight (g)	UPV (m/s)	Weight (g)	UPV (m/s)
0% SSA	4031	4295.8	4011	4259.8	3988	4083.0	3970	3812.5	3850	3505.7
0% SSA	4066	4206.9	4045	4277.7	4048	4155.3	4050	3588.2	3965	3388.9
25%SSA-C	4170	4426.7	4150	4388.5	4145	4326.2	4111	4066.7	4027	3860.8
25%SSA-C	4240	4452.6	4221	4459.1	4228	4363.4	4229	4121.6	4151	3812.5
50%SSA-C	4296	4505.2	4279	4491.9	4270	4433.1	4265	4295.8	4201	4066.7
50%SSA-C	4300	4572.7	4284	4511.8	4275	4407.5	4271	4178.1	4211	4013.2
75%SSA-C	4534	4518.5	4509	4505.2	4504	4485.3	4502	4236.1	4450	4121.6
75%SSA-C	4507	4552.2	4491	4538.7	4485	4511.8	4482	4242.0	4427	4178.1
25%SSA-F	4197	4350.9	4169	4230.2	4163	4127.2	4156	4034.4	4101	3910.3
25%SSA-F	4164	4295.8	4145	4301.8	4138	4195.3	4137	4066.7	4081	3935.5
50%SSA-F	4223	4350.9	4195	4277.7	4182	4247.9	4175	4155.3	4150	3992.1
50%SSA-F	4525	4350.9	4294	4301.8	4277	4265.7	4266	4116.1	4217	4055.9
75%SSA-F	4247	4485.3	4222	4413.9	4218	4369.6	4210	4289.7	4175	4144.0
75%SSA-F	4253	4538.7	4224	4350.9	4227	4369.6	4219	4314.0	4172	4110.5



(a) Control specimen

(b) Concrete specimen with 75% SSA

Figure (7): Comparison of surface appearance after exposure to 250 freeze-thaw cycles: (a) Control specimen; (b) Concrete specimen with 75% SSA

Mass Loss

The mass loss of hardened concrete is usually considered to examine the degree of concrete deterioration under the influence of freezing and thawing (Neville, 1995; He et al., 2016). Table 8 and Figure 8 show the mass loss for concrete specimens exposed to 0, 100, 150, 200 and 250 F/T cycles. The mass loss of hardened concrete specimens increased with the increase in the number of freeze-thaw cycles, while increasing SSA ratios for fine or coarse aggregate substitutes reduced mass loss compared to control specimens for the same cycles of F/T action. For instance, concrete mixes containing 25%, 50% and 75% SSA as substitutes for fine aggregate showed a mass loss of about 2.14%, 2.11% and 1.81% at 250 F/T cycles, respectively, compared to a mass loss of 3.49% for normal-concrete specimens. All concrete specimens containing SSA comply with the requirements for long-term performance and durability of ordinary concrete because their mass losses were less than 5% when exposed to 250 F/T cycles according to GB/T 50082-2009 (GB/T (2009) 50082-2009 (2009)).

Pan et al. (2016) investigated concrete using carbonated ground steel slag aggregate, natural aggregate and recycled steel slag aggregate in salt-water and fresh-water conditions. They found that the characteristics of the interfacial transition zone (ITZ), in terms of the hardness and thickness of the ITZ, have a significant impact on the durability of concrete against the action of freezing and thawing. The results also showed that the resistance to freezing and thawing is enhanced by hydration of steel slag in the cementitious bonding matrix. Besides the aggregate shapes, the coarse aggregate surface increased the interaction between the cement matrix and aggregate and thus a good improvement in ITZ hardness was observed.

Sideris et al. (2018) in their study replaced sand with lines of furnace slag (LFS) in self-compacting concrete (SCC). Their results showed that concrete's resistance to freezing and thawing increases with increasing amount of LFS added to the mixture. The authors concluded that the content of cementitious materials (cement plus LFS) is closely related to performance against freezing and thawing. This was attributed to the improvement of the pore microstructure caused by LFS hydration (Papayianni et al., 2010).

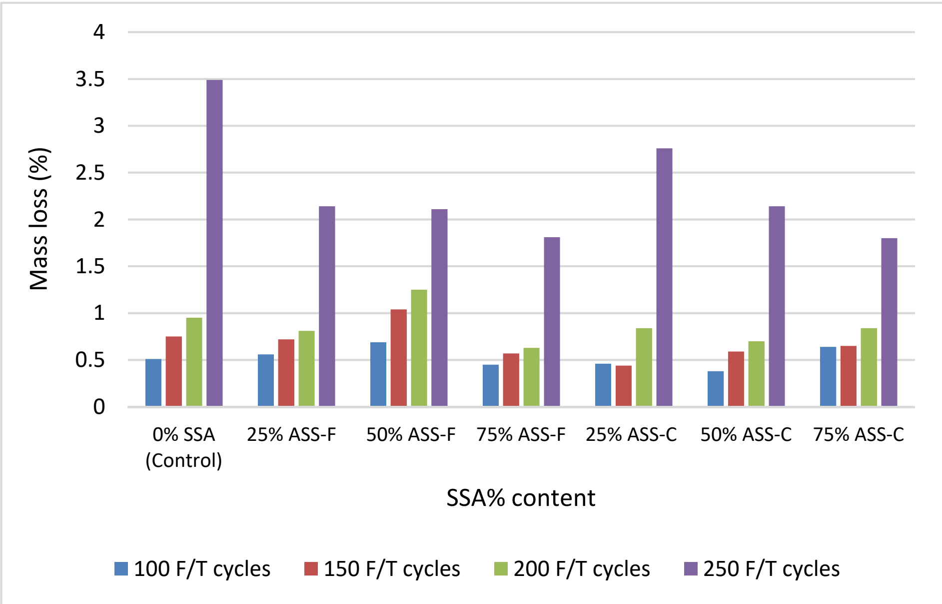


Figure (8): Average mass loss of concrete specimens containing SSA exposed to different F/T cycles

Flexural Strength Loss

The effect of steel slag as fine or coarse aggregate on the loss of flexural strength of concrete under the influence of F/T is shown in Figure 9. The flexural strength of concrete specimens was examined before and after exposure to 250 F/T cycles. The estimated loss in flexural strength of control concrete specimens was 15.77% (0.73 MPa) while incorporation of SSA to replace fine or coarse aggregate reduced the flexural strength loss to no more than 12.96% and 15.33%, respectively. Although internal cracks occur upon interlocking between aggregates (SSA and natural aggregates) due to the fatigue effect of F/T cycles negatively affecting the tensile strength of SCC specimens (Sicat et al., 2014; Ayhan et al., 2011; Allahverdi and Abadi, 2014), the steel slag hydration products within the cementitious material may enhance concrete's resistance to F/T action (Pang et al., 2016). However, the freeze-thaw action can cause the ITZ to expand and separate due to the shrinkage and expansion of the cement paste.

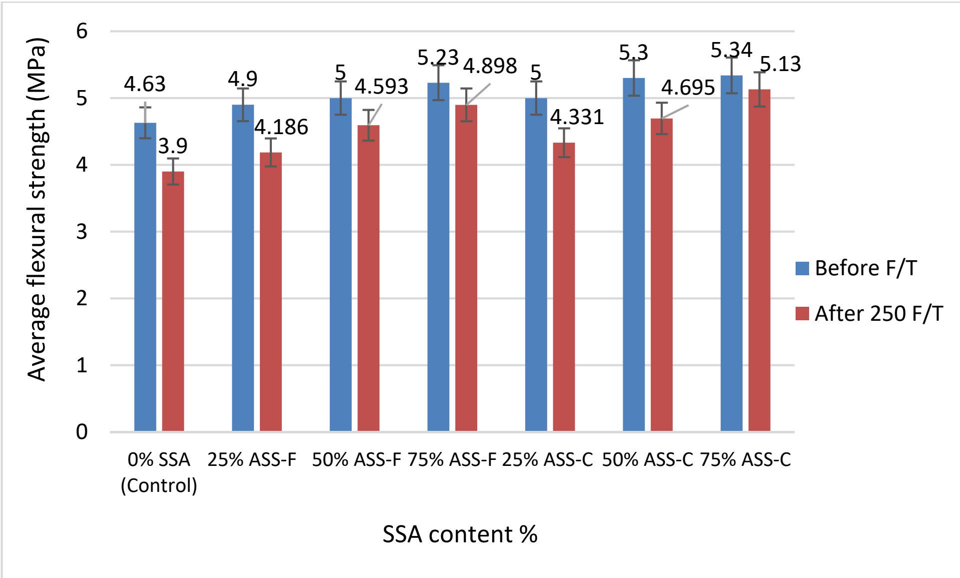
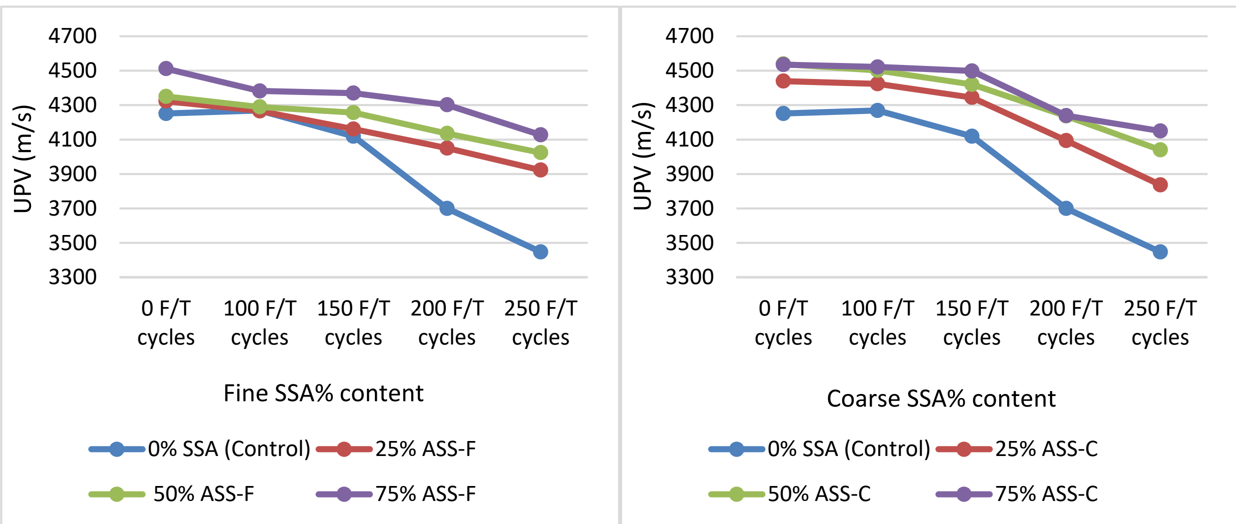


Figure (9): Average flexural strength of concrete specimens containing SSA% before and after 250 F/T cycles

Ultrasonic Pulse Velocity (UPV)

The readings of UPV test for concrete specimens containing different proportions of SSA for partial substitutions of fine or coarse aggregate are shown in Figure 10. The UPV results ranged between 3447 and 4538 m/s under the influence of freeze-thaw action. As seen, the UPV of SSA-containing concrete increased with increasing SSA content, but decreased with increasing number of F/T cycles. The control concrete specimens showed a decrease in UPV by 18.19% (4251.35-3447.3 m/s) after 250 F/T cycles. The incorporation of 75% SSA for fine or coarse aggregate resulted in a better performance as the decrease in UPV was about 8.5%. Also, the UPV results of concrete containing 75% SSA for coarse aggregate showed an excellent quality when exposed to F/T cycles up to 150 and very good quality at 200 and 250 F/T cycles. On the other hand, normal concrete showed very good quality up to 200 F/T cycles exposure and satisfactory at 250 F/T cycles (Whitehurst, 1951).

In their study, Zareei et al (2019) demonstrated that a 30% increase in UPV values occurs when nano-silica and BOFS (25-100%) are used. They concluded that the concrete's durability was enhanced by the secondary C-S-H produced during the reaction between silica in concrete and calcium oxide (CaO) in BOFS.



(a) Fine SSA **(b) Coarse SSA**

Figure (10): UPV of concrete specimens with different SSA% and under action of different F/T cycles: (a) Fine SSA; (b) Coarse SSA

CONCLUSIONS

The use of steel slag in concrete production can be promising in the construction industry. This study investigated the strength and durability of concrete made using large and different proportions of recycled steel slag aggregate to replace natural aggregate (0% to 75% with increments of 25%). The concrete specimens' mass loss, water absorption, permeability and resistance to freezing and thawing (F/T) were studied. The experimental work revealed the following observations and conclusions:

- Partial replacement of fine or coarse natural aggregate with SSA increased the compressive strength of corresponding concrete specimens. The increases in compressive strength ranged from 8% to 21% and 4% to 12% upon replacement with coarse and fine SSA, respectively.
- The incorporation of SSA showed a positive effect on the flexural strength of all concrete mixtures. The highest increase in flexural strength at 15% and 13% was achieved upon coarse and fine SSA replacement, respectively.
- Incorporation of SSA into concrete mixtures results in a denser, less permeable and less water-absorbing concrete. A decrease of about 40% in water permeability was recorded upon replacement of either fine or coarse SSA.
- The inclusion of SSA for fine or coarse aggregate enhances the durability of concrete in terms of resistance to F/T attack as indicated by surface damage, mass loss and flexural strength measurements.
- All concrete specimens containing SSA comply with the requirements for long-term performance and durability of ordinary concrete as stipulated by GB/T 50082-2009 (GB/T (2009) 50082-2009 (2009)).

REFERENCES

Abd El-Hakim, R.T., Elgendy, G.M., El-Badawy, S.M., and Amin, M. (2021). “Performance evaluation of steel slag high-performance concrete for sustainable pavements”. International Journal of Pavement Engineering, 1-19.

Abendeh, R.M., and Baker, M.B. (2020). “Using steel slag aggregate to strengthen self-compacting concrete durability”. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 1-55.

Allahverdi, A., and Abadi, M.M.B.R. (2014). “Resistance of chemically activated high-phosphorous slag content cement against frost-salt attack”. Cold Regions Science and Technology, 98, 18-25.

Arivalagan, S. (2014). “Sustainable studies on concrete with GGBS as a replacement material in cement”. Jordan Journal of Civil Engineering, 8 (3), 263-270.

Arribas, I., Vegas, I., San-Jose, J.T., and Manso, J.M. (2014). “Durability studies on steelmaking slag concretes”. Materials & Design, 63, 168-176.

ASTM C642-97. (1997). “Standard test method for density, absorption and voids in hardened concrete”. ASTM International, West Conshohocken, PA, www.astm.org.

ASTM C597-09. (2009). “Standard test method for pulse velocity through concrete”. ASTM International, West Conshohocken, PA, www.astm.org.

ASTM C666/C666M-15. (2015). “Standard test method for resistance of concrete to rapid freezing and thawing”. ASTM International, West Conshohocken, PA, www.astm.org

ASTM C143/C143M-20. (2020). “Standard test method for slump of hydraulic-cement concrete”. ASTM International, West Conshohocken, PA, www.astm.org.

ASTM C78/C78M-21. (2021). “Standard test method for flexural strength of concrete (using simple beam with third-point loading)”. ASTM International, West Conshohocken, PA, www.astm.org.

Ayhan, M., Gönül, H., Gönül, İ.A., and Karakuş, A. (2011). “Effect of basic pumice on morphologic properties of interfacial transition zone in load-bearing lightweight/semi-lightweight concretes”. Construction and Building Materials, 25 (5), 2507-2518.

Bian, Z., Fang, Y., Yu, F., Wang, X., and Xiang, G. (2021). “Numerical simulation of basic properties of full-steel slag aggregate concrete”. Advances in Civil Engineering.

Biskri, Y., Achoura, D., Chelghoum, N., and Mouret, M. (2017). "Mechanical and durability characteristics of high-performance concrete containing steel slag and crystalized slag as aggregates". Construction and Building Materials, 150, 167-178.

Chandru, P., Karthikeyan, J., and Natarajan, C. (2020). "Steel slag: A strong and sustainable substitute for conventional concreting materials". Sustainable Materials in Building Construction; Springer: Berlin/Heidelberg, Germany, 31-76.

Chen, X., Wang, G., Dong, Q., Zhao, X., and Wang, Y. (2020). "Microscopic characterization of pervious concrete using recycled Steel Slag Aggregate". Journal of Cleaner Production, 254, 120149.

Chunlin, L., Kunpeng, Z., and Depeng, C. (2011). "Possibility of concrete prepared with steel slag as fine and coarse aggregate: A preliminary study". Procedia-Engineering, 24, 412-416.

Das, B., Prakash, S., Reddy, P.S.R., and Misra, V.N. (2007). "An overview of utilization of slag and sludge from steel industries". Resources, Conservation and Recycling, 50 (1), 40-57.

GB/T. (2009). "50082-2009: Standard for test methods of long-term performance and durability of ordinary concrete". China Standard Press, Beijing, China.

Guo, J., Bao, Y., and Wang, M. (2018a). "Steel slag in China: Treatment, recycling and management". Waste Management, 78, 318-330.

Guo, Y., Xie, J., Zheng, W., and Li, J. (2018b). "Effects of steel slag as fine aggregate on static and impact behaviours of concrete". Construction and Building Materials, 192, 194-201.

Guo, Y., Xie, J., Zhao, J., and Zuo, K. (2019). "Utilization of unprocessed steel slag as fine aggregate in normal- and high-strength concrete". Construction and Building Materials, 204, 41-49.

He, Z., Tang, S.W., Zhao, G.S., and Chen, E. (2016). "Comparison of three and one dimensional attacks of freeze-thaw and carbonation for concrete specimens". Construction and Building Materials, 127, 596-606.

Jiang, Y., Ling, T.C., Shi, C., and Pan, S.Y. (2018). "Characteristics of steel slags and their use in cement and concrete: A review". Resources, Conservation and Recycling, 136, 187-197.

Kothei, L., and Malathy, R. (2012). "Mechanical properties of self-compacting concrete with partial replacement of natural sand by steel slag". Int. J. Earth Sci. Eng., 5 (03 (01)), 635-639.

Mineral Commodity Summaries. (2021). "U.S. geological survey". 200 p., https://doi.org/10.3133/mcs2021.

Mo, L., Yang, S., Huang, B., Xu, L., Feng, S., and Deng, M. (2020). "Preparation, microstructure and property of carbonated artificial steel slag aggregate used in concrete". Cement and Concrete Composites, 113, 103715.

Mo, L., Zhang, F., Deng, M., Jin, F., Al-Tabbaa, A., and Wang, A. (2017). "Accelerated carbonation and performance of concrete made with steel slag as binding material and aggregate". Cement and Concrete Composites, 83, 138-145.

Motz, H., and Geiseler, J. (2001). "Products of steel slags an opportunity to save natural resources". Waste Management, 21 (3), 285-293.

Muhmood, L., Vitta, S., and Venkateswaran, D. (2009). "Cementitious and pozzolanic behavior of electric arc furnace steel slags". Cement and Concrete Research, 39 (2), 102-109.

National Minerals Information Center. (2019). "Iron and steel slag statistics and information". (Accessed on 3 May 2021).

Neville, A.M. (1995). "Properties of concrete". Vol. 4. London: Longman.

Nikbin, I.M., Beygi, M.H.A., Kazemi, M.T., Amiri, J.V., Rahmani, E., Rabbanifar, S., and Eslami, M. (2014). "A comprehensive investigation into the effect of aging and coarse aggregate size and volume on mechanical properties of self-compacting concrete". Materials & Design, 59, 199-210.

Palankar, N., Shankar, A.R., and Mithun, B.M. (2016). "Durability studies on eco-friendly concrete mixes incorporating steel slag as coarse aggregate". Journal of Cleaner Production, 129, 437-448.

Pang, B., Zhou, Z., Cheng, X., Du, P., and Xu, H. (2016). "ITZ properties of concrete with carbonated steel slag aggregate in salty freeze-thaw environment". Construction and Building Materials, 114, 162-171.

Papayianni, I., and Anastasiou, E. (2010). "Production of high-strength concrete using high volume of industrial by-products". Construction and building Materials, 24 (8), 1412-1417.

Pellegrino, C., and Gaddo, V. (2009). "Mechanical and durability characteristics of concrete containing EAF slag as aggregate". Cement and Concrete Composites, 31 (9), 663-671.

Peng, Y.C., and Hwang, C.L. (2010). "Carbon steel slag as cementitious material for self-consolidating concrete". Journal of Zhejiang University-Science A, 11 (7), 488-494.

Qasrawi, H. (2012). "Use of relatively high Fe_2O_3 steel slag as coarse aggregate in concrete". ACI Materials Journal, 109 (4).

Qasrawi, H. (2018). "Fresh properties of green SCC made with recycled steel slag coarse aggregate under normal and hot weather". Journal of Cleaner Production, 204, 980-991.

Qasrawi, H. (2020). "Hardened properties of green self-consolidating concrete made with steel slag coarse aggregates under hot conditions". ACI Materials Journal, 117 (1), 107-118.

Saxena, S., and Tembhurkar, A.R. (2018). "Impact of use of steel slag as coarse aggregate and wastewater on fresh and hardened properties of concrete". Construction and Building Materials, 165, 126-137.

Shaiksha Vali, K., Murugan, B.S., Reddy, S.K., and Noroozinejad Farsangi, E. (2020). "Eco-friendly hybrid concrete using pozzolanic binder and glass fibers". International Journal of Engineering, 33 (7), 1183-1191.

Sicat, E., Gong, F., Ueda, T., and Zhang, D. (2014). "Experimental investigation of the deformational behavior of the interfacial transition zone (ITZ) in concrete during freezing and thawing cycles". Construction and Building Materials, 65, 122-131.

Sideris, K.K., Tassos, C., Chatzopoulos, A., and Manita, P. (2018). "Mechanical characteristics and durability of self-compacting concretes produced with ladle furnace slag". Construction and Building Materials, 170, 660-667.

Singh, G., and Siddique, R. (2016). "Effect of iron slag as partial replacement of fine aggregate on the durability characteristics of self-compacting concrete". Construction and Building Materials, 128, 88-95.

Sonebi, M., and Nanukuttan S. (2009). "Transport properties of self-consolidating concrete". ACI Materials Journal, 106 (2), 161-166.

Srinivas, D., Ramagiri, K.K., Kar, A., Adak, D., Farsangi, E.N., and Dutta, S. (2021). "Experimental characterization of quaternary blended mortar exposed to marine environment using mechanical strength, corrosion resistance and chemical composition". Journal of Building Engineering, 102822.

TS EN 12390-8. (2002). "Testing hardened concrete-part 8: Depth of penetration of water under pressure". Institute of Turkish Standards, Ankara, Turkey.

Tsivilis, S., Tsantilas, J., Kakali, G., Chaniotakis, E., and Sakellariou, A. (2003). "The permeability of Portland limestone cement concrete". Cement and Concrete Research, 33 (9), 1465-1471.

Wang, B., and Wu, M. (2020). "Mechanical strengths and durability properties of pervious concretes with blended steel slag and natural aggregate". Journal of Cleaner Production, 271, 122590.

Wang, Q., and Yan, P. (2010). "Hydration properties of basic oxygen furnace steel slag". Construction and Building Materials, 24 (7), 1134-1140.

Whitehurst, E.A. (1951 February). "Soniscope tests of concrete structures". Journal Proceedings, 47 (2), 433-444.

Yu, X., Tao, Z., Song, T.Y., and Pan, Z. (2016). "Performance of concrete made with steel slag and waste glass". Construction and Building Materials, 114, 737-746.

Yildirim, I.Z., and Prezzi, M. (2011). "Chemical, mineralogical and morphological properties of steel slag". Advances in Civil Engineering, 2011.

Zareei, S.A., Ameri, F., Bahrami, N., Shoaei, P., Moosaei, H.R., and Salemi, N. (2019). "Performance of sustainable high-strength concrete with basic oxygen steel-making (BOS) slag and nano-silica". Journal of Building Engineering, 25, 100791.