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A Comprehensive Investigation of Performance Characteristics, Mechanical Properties and Durability Parameters of Self-compacting Concrete Containing Iron Slag as Coarse Aggregate

Ali Poornamazian[1], Mohsen Izadinia[1*]

[1] Department of Civil Engineering, Najafabad Branch, Islamic Azad University, 85141-43131 Najafabad, Iran
[*] Corresponding author, e-mail: izadinia@iaun.ac.ir

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Abstract

In this paper, iron slag is used as partial coarse aggregate substitution in Self-compacting concrete (SCC). The SCC samples tests were conducted after 28 days of water curing for samples with 0%, 10%, 20%, 30%, 40%, 50%, and 60% iron slag as coarse aggregate substitutes. This paper evaluates slump flow, V-funnel, L-box, compressive strength, flexural strength, splitting tensile strength, surface water absorption, capillary water absorption, electrical resistance, acid resistance, and ultrasonic pulse velocity (UPV) of concrete samples. Furthermore, scanning electron microscopy (SEM) of samples was investigated for evaluating cement paste microstructure. Samples containing 20%, 60%, and 60% iron slag as coarse aggregate substitute have higher compressive, flexural, and splitting tensile strength than control samples (about 18.4%, 28.6%, and 16.9% higher, respectively). In addition, using 10%, 20%, 30%, and 40% iron slag as coarse aggregate increased the compressive strength. Moreover, incorporating iron slag as a coarse aggregate decreased the mass loss of samples which were exposed to the acid environment compared to control specimens. Using iron slag as partial coarse aggregate substitution reduced the porosity of the cement matrix compared to control samples (based on SEM images).

Keywords

self-compacting concrete, iron slag aggregate, coarse aggregate, mechanical strength, durability

1 Introduction

Concrete is an extensively utilized construction material in today's contemporary era. However, the conventional constituents used in its production give rise to significant environmental challenges. To promote sustainability in the construction industry, it is crucial to incorporate industrial waste materials that possess similar properties to conventional materials and meet the required code specifications into concrete [1, 2]. The sustainability of natural sand and gravel is being threatened by overusing natural resources for construction, which has a number of detrimental effects on the other side, dumping industrial waste on land pollutes the ecosystem and worsens environmental problems. To manage solid industrial waste and lessen the exploitation of natural resources, numerous researchers are working tirelessly to dump industrial trash into the construction industry [3]. Numerous industries are currently disposing of a wide range of waste materials into the environment. These waste materials include ceramic and brick waste, waste glass, construction demolition waste, steel slag, dolomite residual powder, weld slag, marble powder, red mud, marble powder, spent garnet sand, granite sawing waste, rubber waste, ladle furnace slag, perlite powder, copper slag, plastic waste, iron slag, and foundry sand. Interestingly, these waste materials can be utilized effectively as partial replacements for cement, sand, and gravel in both regular concrete and self-compacting concrete [4]. By incorporating these waste materials, the construction industry can not only mitigate environmental concerns but also enhance the sustainability and performance of concrete structures [5, 6].

Self-compacting concrete (SCC) is produced using conventional materials along with the inclusion of superplasticizers and viscosity-modifying agents. This type of concrete showcases distinctive characteristics, including

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excellent workability, exceptional passing ability, and strong resistance to segregation in its fresh state [7]. While SCC contains a smaller proportion of aggregates compared to Normally Vibrated Concrete (NVC), they still play a significant role in determining both the fresh and hardened properties of the concrete. In recent times, the concrete industry has been increasingly adopting alternative materials for the production of SCC, marking a shift towards more sustainable practices [8]. Extensive research has been conducted on incorporating industrial waste and by-product materials into self-compacting concrete, and numerous studies have determined that adding such waste and by-product materials in specific proportions enhances their mechanical properties, microstructure, and overall durability [9]. Among of these wastes and by product materials, iron slag is considered as cement and aggregate partial replacements. Large amounts of iron slag are produced by the iron and steel industry each year in various companied worldwide [10]. India produces approximately 17,000 tons of iron slag (IS) annually [11]. Unfortunately, a large volume of iron slag is often disposed of in open areas near human settlements, posing significant risks to living beings. However, utilizing iron slag in the manufacturing of concrete presents a favorable solution to its disposal problem. Given the continuous growth in iron slag production, it becomes essential and suitable to incorporate it into concrete instead of disposing of it. Many researchers have devoted their efforts to studying the use of iron slag as a supplementary material, replacing sand in concrete. In the case of SCC, replacing aggregate with iron slag has shown promising results in terms of strength and microstructural properties [12].

Ibrahim et al showed that using these materials instead of aggregates leads to an increase in shielding properties against 137Cs and 60Co point sources. Also, the use of these materials can increase the strength of concrete [13]. Also, Baalamurugan et al. [14] showed in a study that concretes containing slag aggregates can be a cost-effective alternative to radiation shielding composites. Teymouri et al. [15] investigated the engineering properties of iron slag concrete and its ability to reduce urban runoff pollution. In this article, it was shown that this concrete requires a little less mixing and implementation cost than normal concrete, it is recommended for collecting urban runoff and increasing its quality in urban areas with low traffic load. Vijayaraghavan et al. [16] in a study replaced concrete aggregates with copper and iron slag. In this study, it was shown that the use of these materials can improve the mechanical properties of concrete. In a study, Singh and Siddique [17] investigated the effect of different percentages of iron slag instead of aggregates on mechanical properties. The studied properties were slump flow, V-funnel, U-box, L-box, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity. The results of this article show that the use of iron slag can lead to the improvement of properties such as compressive strength, splitting tensile strength, and flexural strength in SCC. In another study, Díaz et al. [18] replaced iron slag with fine aggregate in SCC. Also, in this study, the effects of nano-silica on the properties of concrete were also investigated. In this study, it was shown that samples with iron slag at an early age (7 days) have higher compressive strength.

Slag concretes offer numerous advantages in construction, making them a versatile choice for various building components. In foundations and basement walls, where moisture and potential soil contaminants are concerns, slag concretes' durability and resistance to chemical attacks provide long-lasting structural integrity. They ensure that these critical building elements can withstand environmental stressors, protecting the entire structure. Slag concretes improve pavement durability, extending its lifespan and reducing maintenance costs. Moreover, in infrastructure projects such as bridges, tunnels, and marine structures, where exposure to harsh environments is inevitable, slag concretes' resistance to corrosion and reduced maintenance requirements make them a preferred choice, contributing to the longevity and sustainability of these essential elements of the built environment [19].

The present work aimed to assess the effects of iron slag as a natural coarse aggregate substitute. Concrete samples were made by incorporating 0%, 10%, 20%, 30%, 40%, 50%, and 60% iron slag as natural coarse aggregate substitute. Curing concrete samples was performed in water for 28 days. Several experimental tests were conducted, including slump flow, V-funnel, L-box, compressive strength, flexural strength, splitting tensile strength, surface water absorption, capillary water absorption, electrical resistance, acid resistance, and ultrasonic pulse velocity (UPV), and micro-scale analysis like scanning electron microscopy (SEM). Samples containing 20%, 60%, and 60% iron slag as a coarse aggregate substitute have higher compressive, flexural, and splitting tensile strength than control samples (about 18.4%, 28.6%, and 16.9% higher, respectively). In addition, using 10%, 20%, 30%, and 40% iron slag as a coarse aggregate increased the compressive strength and decreased the mass loss of samples which were exposed to the acid environment compared to control specimens.

2 Materials

2.1 Cement

In this article, type 2 Portland cement based on ASTM C150 is used [20]. The physical and chemical characteristics of the Portland cement as well as cement phases were obtained by XRD (Rietveld method) and the results are presented in Table 1. It should be noted that the chemical characteristics of the Portland cement were assessed with X-ray fluorescence (XRF) analysis.

2.2 Limestone powder (LSP)

This study utilized limestone powder of 95% purity. The physical and chemical attributes of the limestone powder are outlined in Table 2. It is worth mentioning that the chemical properties of the limestone powder were evaluated using X-ray fluorescence (XRF) analysis.

2.3 Natural coarse and fine aggregate

The characteristics of the natural fine and coarse aggregates are presented in Table 3, following the standards ASTM C 29-09 [21], ASTM C 127-07 [22], and ASTM C 128-07 [23]. The coarse aggregates, with a maximum diameter of 19 mm, were produced by crushing boulders found in Isfahan City, Iran. The gradation of the natural aggregates and iron slag is illustrated in Fig. 1.

Table 1 Physical and chemical characteristics of Portland cement (type II)

Chemical compositions (%)		Physical characteristics	
SiO_2	24	Water absorption (%)	-
Al_2O_3	6	Specific density (kg/m^3)	3050
Fe_2O_3	5	Specific surface area (m^2 /kg)	312
CaO	60	Autoclave expansion (%)	0.1
MgO	0.3		3 days 26
K_2O	0.8	Compressive strength (MPa)	7 days 30
Na_2O	0.7		28 days 44
SO_3	1.5	Initial setting time (min)	90
LOI (loss on ignition)	1.3	Final setting time (min)	150
Cement phases (%)			
C_3S	54	-	-
C_2S	20	-	-
C_3A	9	-	-
C_4AF	11	-	-
Gypsum	6	-	-

Table 2 Chemical and physical characteristics of limestone powder (LSP)

Chemical composition	LSP (%)	Physical properties	LSP (%)
SiO_2	0.13	Water absorption (%)	0.2
Al_2O_3	0.06	Specific density (kg/m^3)	2600
Fe_2O_3	0.01	Specific surface area (m^2/kg)	1680
CaO	55	$CaCO_3$ (%)	95
MgO	0.7	-	-
K_2O	0.05	-	-
Na_2O	0.05	-	-
SO_3	0.01	-	-
LOI (loss on ignition)	43.5	-	-

Table 3 Characteristics of used natural aggregates and IS

Component	Properties		
	Appearance	Specific gravity	Water absorption (%)
Fine aggregate	Light grey	2.58	1.12
Coarse aggregate	Grey	2.81	0.37
IS aggregate	Black, Glassy texture	3.34	0.24

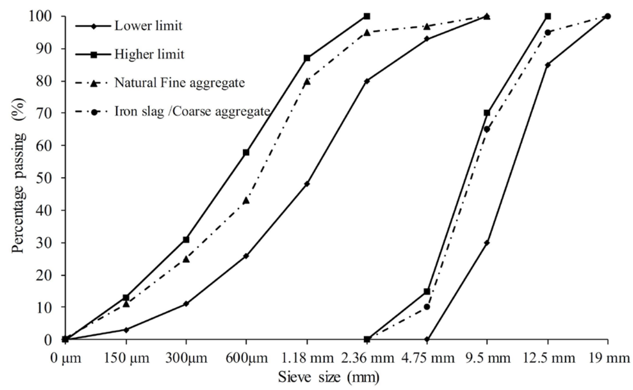

Fig. 1 Fine and coarse particle size distributions of IS and natural aggregates

2.4 Iron slag

Iron Slags are known as the primary waste produced by the steel industry. The visual representation of the iron slag aggregate utilized in this research can be found in Fig. 1. The water absorption rate of the iron slag is 0.24%, and its specific gravity is 3340 kg/m^3. The particle size of the iron slag ranges between 4.75 and 19 mm, and the distribution of grain sizes are illustrated in Fig. 1. The primary components of these materials consist of approximately 8.3% SiO_2, 4.3% Al_2O_3, 57.2% Fe_2O_3, 21.85% CaO, and 2.5% MgO.

2.5 Super-plasticizer (SP)

In order to improve the workability of fresh cement mortar, a high-range water reducer called P10-3R based on

Table 4 The super-plasticizer properties base on ASTM C494 [24]

Items	Standards quality	Testing results
Density (g/cm^3)	0.94–1.15	1.11 ± 0.02
PH	5.4–7.4	7.2
Chlorine (ppm)	< 2400	750
Color	-	Brown

polycarboxylic ether (HRWR) has been used. The properties of super-plasticizer are presented in Table 4 based on ASTM C494 [24].

3 Sample preparation

A total of 7 different mix designs were prepared, each with varying percentages (0%, 10%, 20%, 30%, 40%, 50%, and 60%) of natural coarse aggregates replaced by Iron slag. These mix designs were named SCC0, SCC10, SCC20, SCC30, SCC40, SCC50, and SCC60. The SCC0 mix served as the control group; containing no Iron slag as coarse aggregate and SCC60 containing 60% Iron slag as coarse aggregate. Additionally, a High-Range Water-Reducing (HRWR) admixture was used in a ratio of 0.9% (relative to the cement weight). It should be noted that the ratio of water/cement was kept constant for all mixtures. The details of the mix proportions and of mixes can be found in Table 5.

4 Testing the specimens

4.1 Fresh concrete experiments

To assess the workability of the SCCs, a series of tests were conducted following the guidelines outlined in the code. The tests carried out included the slump flow test, V-funnel test, and L-box test according to the EFNARC [25] code recommendations (Table 6).

4.2 Hardened concrete experiments

A comprehensive series of tests was conducted on the materials under consideration, following the relevant standards and codes. The tests performed included compressive strength, split tensile strength, flexural strength, surface water absorption, capillary water absorption, acid resistance, electrical resistance, and ultrasonic pulse velocity tests. In Fig. 2, Iron slag and the strength tests are shown. The compressive strength test was conducted on three cubic specimens with dimensions of 100 mm, in accordance with BS: Part 116 [26]. The test was performed after 28 days of curing, using a loading rate of 2.5 kN/s. For the split tensile strength test, three cylindrical specimens were used, and the test was performed after 28 days of water curing. The loading rate applied during the test was 2.1 kN/s, as per the requirements of ASTM C496 [27].

Table 5 Mix proportions of SCC

Component (Kg/m^3)	SCC0	SCC10	SCC20	SCC30
Cement	335	335	335	335
Limestone powder	105	105	105	105
Superplasticizer (kg)	3	3	3	3
Natural fine aggregate	940	950	950	950
Natural coarse aggregate	820	738	656	574
Iron slag coarse aggregate	0	82	164	246
Water/Cement (%)	0.49	0.49	0.49	0.49
Iron slag (%)	0	10	20	30
Component (Kg/m^3)	**SCC40**	**SCC50**	**SCC60**	
Cement	335	335	335	
Limestone powder	105	105	105	
Superplasticizer (kg)	3	3	3	
Natural fine aggregate	950	950	950	
Natural coarse aggregate	492	410	328	
Iron slag coarse aggregate	328	410	492	
Water/Cement (%)	0.49	0.49	0.49	
Iron slag (%)	40	50	60	

Table 6 Acceptance criteria for SCC according to EFNARC [34]

Slump flow test	
Slump flow classes	Slump flow (mm)
SF1	550–650
SF2	660–750
SF3	760–850
V-funnel test	
Viscosity classes	V-funnel times (s)
VF1	≤ 8
VF2	9–25
L-box test	
Passing ability classes	Blocking ratio (h2/h1)
PA1	≥ 0.8 with 2 bars
PA2	≥ 0.8 with 3 bars

The bending strength test, based on the three-point bending method outlined in ASTM C78 [28], was conducted on three beams with dimensions of 500 mm × 100 mm × 100 mm. The average strength of the three beams at 28 days was determined, and a loading rate of 0.2 kN/s was applied during the test. Surface water absorption tests were carried out on two cubic samples with dimensions of 100 mm, following the guidelines of BS: Part 122 [29]. Ultrasonic pulse velocity tests were performed in accordance with ASTM C597 [30]. In addition, capillary water absorption, acid resistance, and electrical resistance tests were conducted based on the research papers published by Hall [31], Kannan and Ganesan [32], and Mendes et al. [33], respectively [34].

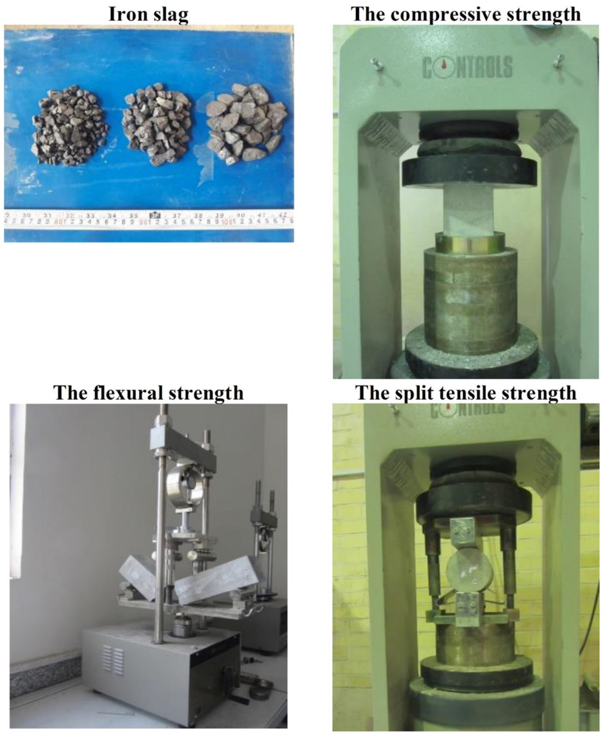

Fig. 2 Iron slag and the strength tests

5 Results and discussions

5.1 Fresh concrete experiments

5.1.1 Slump flow

The effect of using iron slag on concrete slump is shown in Fig. 3. The slump values of concretes range from 658 to 764 mm. As observed in Fig. 3, with an increase in slag volume in concrete, the slump value has significantly increased. The slump values of concrete mixtures containing 10%, 20%, 30%, 40%, 50%, and 60% iron slag have improved by 3.51%, 5.32%, 7.90%, 10.79%, 13.22%, and 16.2%, respectively, compared to the control sample. This can be related to the less water absorption of slag grains is that the amount of free water in concrete increases and in fact the ratio of water to cement increases and this will increase the amount of concrete slump. It should be mentioned concrete mixtures made with 0-50% steel slag fall into the SF2 category according to EFNARC classification. In contrast, the sample containing 60% iron slag would be classified under the SF3 group. Based on the slump test results, concretes containing higher percentages of slag can be used for the production of structural members where concrete needs to flow, such as beams with different cross-sections. Biskri et al. [35] suggest that in some types of slag, the uneven surface and broken particles can decrease the slump value of concrete.

5.1.2 L-box

Fig. 4 represents the values of the L-box ratio for all designs containing different percentages of coarse iron slag. The blocking ratio (h_1/h_2) for concretes which were produced with 0 to 60 percentage of steel slag as coarse aggregate ranges from 0.87 to 0.98. Generally, as the amount of iron slag increases, the L-box ratio increases, and the ability of concrete to pass through rebar improves. The parameter value of h_1/h_2 for designs containing 10, 20, 30, 40, 50, and 60 % iron slag, compared to the control design, has increased by 2.3%, 3.45%, 6.93%, 9.21%, 11.5%, and 12.64%, respectively. According to the EFNARC classification, all concretes which were produced with iron slag fall into the PA1 category and meet the requirements of passing and filling ability. The glassy texture and low water absorption of coarse iron slag particles have reduced the viscosity of the concrete and increased the water-to-cement ratio, allowing the concrete to easily pass through the compactness of the rebars. In higher volumes, due to the sharp angular shape of the slag particles and the increased probability of blocking, the rate of improvement in passing ability has decreased. Sharifi et al. [36] also reported that the use of slag as a substitute for natural coarse aggregates increases the L-box ratio and passing

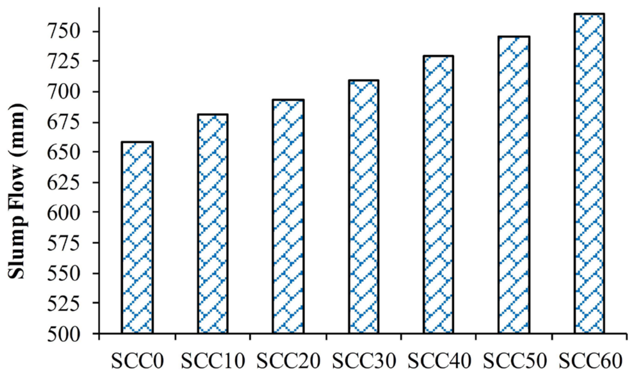

Fig. 3 Slump flow results of SCCs

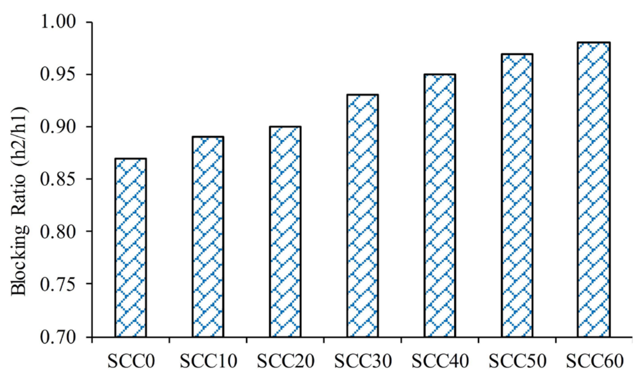

Fig. 4 L-box results of SCCs

ability. Rehman et al. [1] claimed that replacing natural aggregates in concrete with 60 and 80 percent iron slag results in a decrease in the passing ability due to the higher weight of slag compared to natural aggregates in concrete.

5.1.3 V-Funnel test

The values of the V-Funnel test of concrete samples were made by 0–60% iron slag as coarse aggregate are shown in Fig. 5. All the concrete samples demonstrated a range of time between 3.96 seconds and 6.1 seconds to pass through the funnel, as depicted in Fig. 5. With the increasing replacement of iron slag as coarse aggregate, all the mix designs exhibited shorter passage times of the funnel test than the control design. This can be attributed to the shape and angularity of the iron slag grains, which made concrete difficult to pass through the funnel. It should be mentioned that during the test, no instability or segregation was observed, indicating that the concrete mixture's viscosity was appropriate. According to the EFNARC [25] classification, all concretes produced with iron slag fall into the VF1 category in terms of funnel time.

5.2 Hardened concrete experiments

5.2.1 Compressive strength

The compressive strengths of specimens after 28 days of water curing are presented in Fig. 6. The results demonstrate that using iron slag up to 20% improves the compressive strength of concrete samples compared to other mixes. This can be related to the steel slag that characterized by a rough surface and high angularity, exhibits superior mechanical bite force and cohesive force compared to regular natural sand. As a result, it forms a stronger bond with cement paste, leading to higher bonding strength [37]. As it can be observed, the compressive strength of mixes SCC50 and SCC60 decreased compared to control samples (4.3% and 9.5%, respectively).

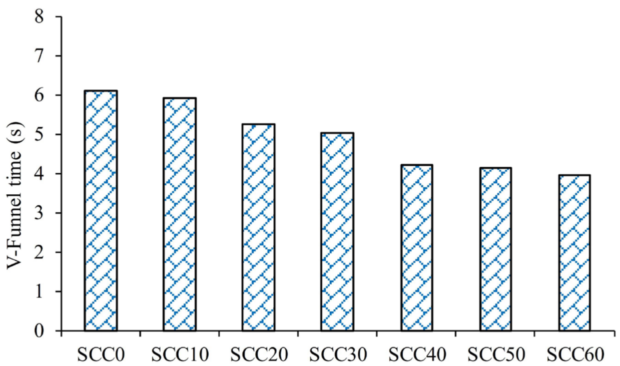

Fig. 5 V-Funnel results of SCCs

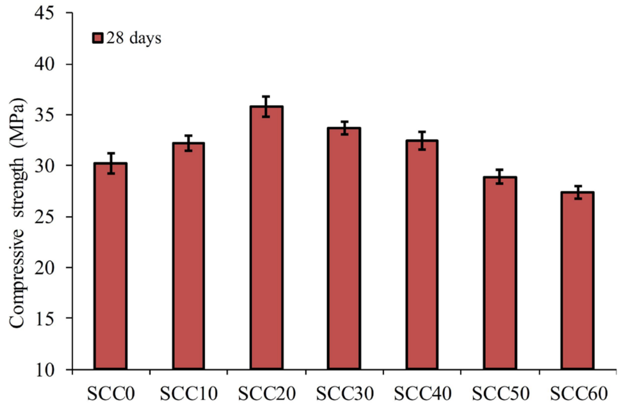

Fig. 6 Compressive strength results of SCCs

The decrease in compressive strength observed in concrete mixes using high percentage steel slag aggregates could be attributed to the development of a calcite coating on the surface of the aggregates [38]. This coating hampers the bond between the paste and aggregates, which plays a crucial role in determining the properties of concrete. When the bond strength between the paste and coating layer is stronger compared to the bond between the coating layer and aggregate surface, a weak aggregate-coating interface is formed. This weak interface has a negative impact on the mechanical and durability properties of concrete mixes, as explained by Forster [39]. Furthermore, as mentioned in slump flow section the less water absorption of slag grains is that the amount of free water in concrete increases and in fact the ratio of water to cement increases. In other words, free water in the concrete samples incorporating iron slag as coarse aggregate increased. Several studies have reported that incorporating slag as coarse aggregate in concrete reduces compressive strength due to the presence of excess free water [40, 41]. Sharma and Khan [42] have explained that water in concrete containing high volumes of slag tends to migrate towards the surface, leading to the formation of capillaries, voids, and fine cracks in the cement paste, particularly in the interfacial transition zones (ITZs), resulting in a reduction in concrete strength.

5.2.2 Flexural strength

Fig. 7 shows the results of the flexural strength test conducted on concrete samples containing varying percentages of iron slag as coarse aggregate after 28 days of water curing. Fig. 7 indicates that iron slag inclusion in self-compacting concrete (SCC) contributed to enhanced flexural strength. The flexural strength values for all specimens fell within the range of 3.74 to 4.81 MPa. Mix SCC0 exhibited

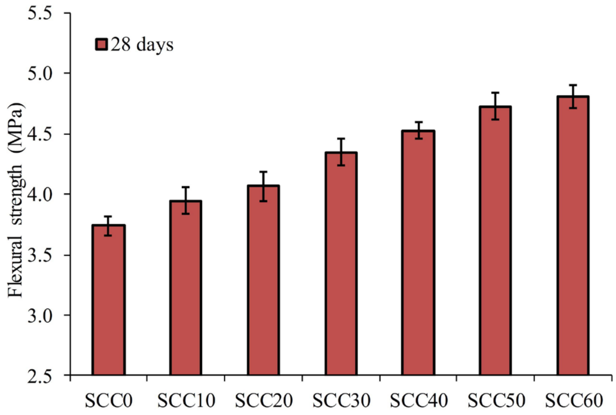

Fig. 7 Flexural strength results of SCCs

the lowest flexural strength, while SCC60 demonstrated the highest flexural strength. By incorporating 10%, 20%, 30%, 40%, 50%, and 60% iron slag as coarse aggregate, the flexural strength improved by approximately 5.6%, 8.8%, 16.3%, 21.1%, 26.5%, and 28.6% compared to the control sample, respectively. As it can be observed, the improvement rates of flexural strength were increased in specimens containing more iron slag as coarse aggregate. This can be attributed to the angular shape of iron slag aggregates, which led to form a stronger bond with cement paste, leading to higher bonding strength [37]. Additionally, high hardness of slag grains plays a significant role in augmenting the flexural strength. In other words, when a crack encounters the slag grains which have a high hardness, it must pass through the surrounding environment of these grains and the crack path will be winding. This phenomenon improves the flexural strength and increases the resistance against crack propagation [15, 43, 44].

5.2.3 Split tensile strength

Fig. 8 illustrates the results of split tensile strength tests that were conducted on both the control sample and self-compacting concretes (SCCs) incorporating iron slag as coarse aggregate. By using 10%, 20%, 30%, 40%, 50%, and 60% iron slag as coarse aggregate, the split tensile strength improved by 2.03%, 6.08%, 9.46%, 11.15%, 15.88%, and 16.89% compared to the control sample, respectively. This can be related to the steel slag that characterized by a rough surface and high angularity, exhibits superior mechanical bite force and cohesive force compared to regular natural sand. As a result, it forms a stronger bond with cement paste, leading to higher bonding strength [37]. It is worth noting that split tensile strength is more sensitive to changes in surface texture compared to compressive strength. Previous studies examining the replacement of natural aggregates with slag have also reported an increase in split strength with increased slag content [42, 45]. A replacement of 60% of natural aggregates with slag has been considered an optimal value in some studies [42, 46]. However, other studies have indicated that using 100% slag as aggregates enhances the tensile strength of concrete compared to the control mix design [46, 47].

5.2.4 Surface water absorption

Fig. 9 presents the results of surface water absorption for iron slag samples. Generally, all mixtures containing coarse iron slag particles showed lower surface water absorption than the control mixture. The overall surface water absorption values for all samples at different ages ranged from 0.09% to 2.28%. The mix containing 40% slag exhibited the lowest surface water absorption. The surface water absorption values for all concrete mixes including 10–60% iron slag at 1 hour, 1 day, 7 days, and 28 days showed a reduction of 2.15–3.55%, 4.17–33.26%, 3.70–28.49%, and 2.81–26.63%, respectively, compared to the control mixes. The improvement in the hydration process due to the increase in excess water in concrete resulted in the filling of voids and the sharp angular shape of iron slag particles, which led to the interruption

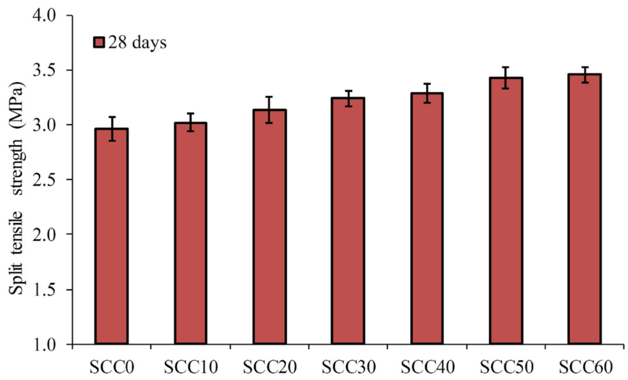

Fig. 8 Split tensile strength results of SCCs

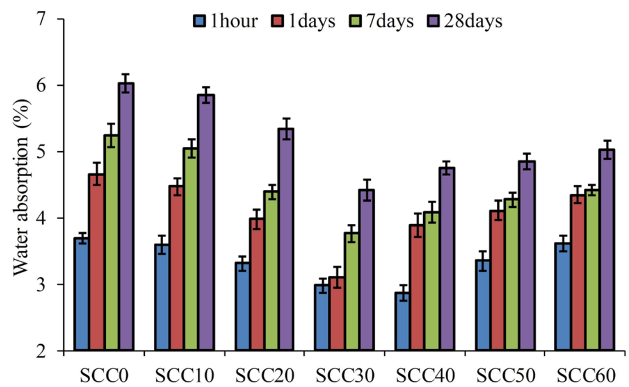

Fig. 9 Surface water absorption results of SCCs

of capillary channels in the concrete and reduced surface water absorption. Palankar et al. [38] claim that when replacing 100% of natural aggregates with slag, the increase in surface water absorption in concrete is negligible. Sheikh et al. reported that the surface water absorption of concrete containing 60% slag decreases compared to control samples at 1 hour, 7 days, and 28 days [48].

5.2.5 Capillary water absorption

The water absorption values of specimens containing 0–60 percent iron slag at different durations of 0.5, 1, 5, and 24 hours are shown in Fig. 10. The presence of iron slag particles has resulted in a decrease in the water absorption (sorptivity) of concrete compared to concrete made with natural aggregates. The decreasing trend in water absorption has been observed up to 30 percent replacement at 0.5 hours. However, at 1, 5, and 24 hours, the decreasing trend in water absorption occurred up to 40 percent replacement. Despite a slight increase in the replacement percentages of 50 and 60 percent, the water absorption of the specimens is still lower than that of the control specimens. The percentage decrease in this parameter at 0.5, 1, 5, and 24 hours of testing, compared to the control specimens, is respectively shown as 12.56-36.68%, 6.25-38.19%, 22.01-54.11%, and 19.21-79.46%. With an increase in the testing duration from 0.5 to 24 hours, the water absorption values for concretes containing 0, 10, 20, 30, 40, 50, and 60 percent iron slag have decreased by 80.42%, 81.91%, 83.51%, 84.48%, 80.83%, 89.32%, and 80.1%, respectively. As seen in Fig. 10, the use of iron slag as a coarse aggregate significantly reduces concrete capillary water absorption. It should be noted that slag, due to enhancing the hydration process, fills the voids and capillaries, thereby reducing water absorption. The presence of sharp-edged slag particles also interrupts the capillaries, leading to a tortuous path and consequently reducing water absorption. Biskri et al. [35] suggested the use of supplementary cementitious additives such as silica fume to control the partial increase in water absorption in concretes containing higher percentages of slag. In this case, the capillary voids are filled by hydration products such as C-S-H, improving the porous structure of concrete and significantly reducing the rate of water absorption.

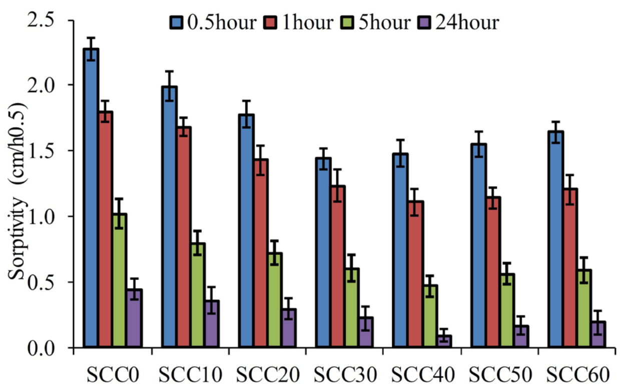

Fig. 10 Capillary water absorption results of SCCs

5.2.6 Electrical resistance

The electrical resistance of samples containing iron slag aggregates is shown in Fig. 11. Concrete mixes containing 10, 20, and 30 percent slag have increased electrical resistance in comparison to control concrete. However, concrete mixes with 40-60 percent slag exhibit a significant decrease in electrical resistivity and demonstrate lower resistivity than control concrete. The mix with 20 percent slag has the highest electrical resistance (48.3 percent higher than the control sample). However, concrete made with 60 percent slag shows a 65.5 percent decrease in electrical resistance compared to the control sample. It is evident that higher electrical resistance indicates a denser structure and fewer interconnected pores. The increase in water content in mixes with percentages higher than 30 leads to the creation of a more porous structure and reduces electrical resistance.

5.2.7 Acid resistance

The values of weight loss and reduction in strength of concrete samples which were made by 0–60% iron slag are shown in Table 7. The weight loss values for concrete mixtures containing 0%, 10%, 20%, 30%, 40%, 50%, and 60% iron slag are 1.73%, 0.83%, 0.59%, 1.05%, 1.41%, 1.88%, and 2.31%, respectively. As observed, the weight loss in samples containing 50% and 60% slag is higher than control concrete. The extent of surface deterioration in mixtures consisting of 10% and 20% slag was very minimal and hardly noticeable. In these samples, the appearance

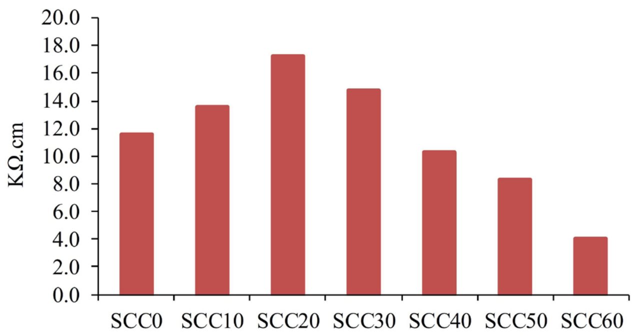

Fig. 11 Electrical resistance results of SCCs

Table 7 Acid resistance results of SCCs

Mixtures	Weight (before acid curing)	Weight (after acid curing)	Mass loss
SCC0	2278	2239	-1.73
SCC10	2297	2278	-0.83
SCC20	2308	2294	-0.59
SCC30	2325	2301	-1.05
SCC40	2348	2315	-1.41
SCC50	2360	2316	-1.88
SCC60	2309	2256	-2.31
Mixtures	Compressive strength (before acid curing)	Compressive strength (after acid curing)	Strength reduction
SCC0	30.23	28.95	-4.23
SCC10	32.18	31.69	-1.52
SCC20	35.78	35.37	-1.15
SCC30	33.69	33.01	-2.02
SCC40	32.45	31.44	-3.11
SCC50	28.92	27.63	-4.46
SCC60	27.36	25.42	-7.09

mostly exhibited localized corroded areas. Generally, immersing the samples in an acid environment resulted in a decrease in compressive strength compared to curing in water. The highest reduction in strength belongs to concrete with 60% slag at 7.09, while concrete with 20% slag has the lowest reduction at 1.15%. It should be noted that with the immersion of the samples in an acidic environment, the pH value decreases and releases a higher amount of calcium, affecting the structure and composition of C-S-H (calcium silicate hydrate) phases. When the pH value decreases further, the C-S-H structure becomes unstable, releasing more lime, causing weight loss and reduced strength. Palankar et al. Stated that the replacement of natural aggregates with slag in higher volumes results in decreased strength in acidic environments [38]. In Fig. 12, a concrete sample is shown after exposure to an acidic environment.

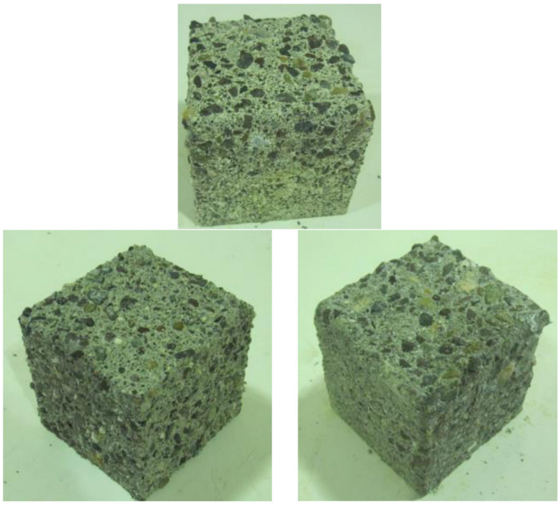

Fig. 12 Concrete sample after being exposed to the acid environment

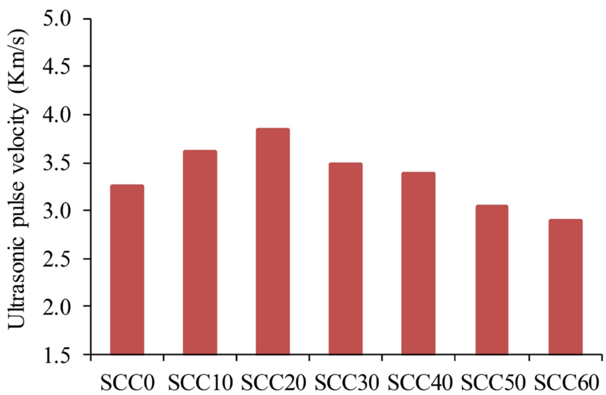

Fig. 13 UPV results of SCCs

5.2.8 Ultrasonic pulse velocity (UPV)

Fig. 13 shows the ultrasonic pulse velocity (UPV) values of concrete specimens after 28 days of water curing. The specimens containing 20% iron slag as coarse aggregate exhibited the highest UPV values compared to other specimens. However, the mix including 60% iron slag exhibited the lowest UPV values compared to other specimens. As can be seen, UPV values of mixes SCC50 and SCC60 decreased compared to control samples (6.8% and 11.1%, respectively). Compressive strength results showed a similar trend. According to the slump flow section, the slump flow of concrete samples increased as more iron slag replaced natural coarse aggregate. These results indicate that free water in concrete samples incorporating iron slag as coarse aggregate increased. Several studies have reported that incorporating slag as coarse aggregate in concrete reduces compressive strength due to the presence of excess free water [40, 41, 47]. In other words, the presence of higher free water decreases the compressive strength and increases the porosity of concrete samples, and as a result reduces sound wave transfer velocity within the material.

5.2.9 SEM

In this study, SEM images were used to examine the microstructure of concrete specimens with and without iron slag. As shown in Fig. 14, voids and porous structures are observed in the mix SCC0, which can affect its strength and durability. However, in the SCC20 design (Fig. 14), a highly cohesive and uniform concrete surface is observed compared to the control sample. These results

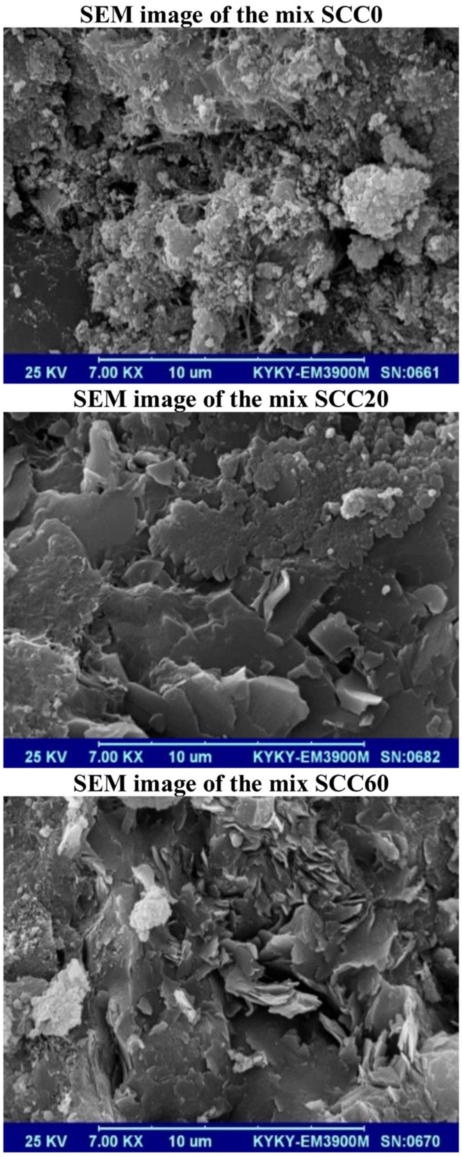

Fig. 14 SEM image of the mixes

can be attributed to increased hydration products, especially C-S-H gel, which fill the voids and block the pathways of capillary channels. Additionally, in the SCC60 design, the amount of voids and porosity increases, leading to a decrease in concrete specimen strength and durability. In other sections, a laminar structure of hydration products is also observed, which is not expected to bear load or withstand pressure. These observations could be the reasons for the compressive strength results that were presented in Section 5.2.1. Brand and Roesler [49] argue that concrete containing slag has a more uniform amount of calcium hydroxide in the interfacial transition zone (ITZ) compared to concrete with natural aggregates, and they also have lower porosity. Afshoon et al. [50] stated that in concrete containing higher percentages of slag, due to their low water absorption and smooth surface, the amount of free water in the concrete increases significantly. This, in turn, creates microblading conditions and increases the thickness of the ITZ around the aggregates, leading to the formation of numerous cracks and capillary channels.

6 Conclusions

The present study analyzed the performance of samples in which iron slag was utilized as a coarse aggregate replacement. The study evaluated the fresh and hardened characteristics of concrete samples like slump flow, V-funnel, L-box, compressive strength, flexural strength, splitting tensile strength, surface water absorption, capillary water absorption, electrical resistance, acid resistance, and ultrasonic pulse velocity (UPV), and micro-scale analysis like scanning electron microscopy (SEM). Based on the obtained results, the following conclusions were drawn:

- With an increase in slag volume in concrete, the slump value has significantly increased. Based on the slump test results, concretes containing higher percentages of slag can be used for the production of structural members where concrete needs to flow.
- As the amount of iron slag increases, the L-box ratio increases, and the ability of concrete to pass through rebar improves.
- With the increasing replacement of iron slag as coarse aggregate, all the mix designs exhibited shorter passage times of the funnel test than the control design.
- Mixes SCC60 and SCC20 exhibit the lowest and highest compressive strengths, respectively. The specimens' compressive strength ranges from 27.36 to 35.78 MPa after 28 days of water curing. Moreover, the compressive strength of mixes SCC50 and SCC60 decreased compared to control samples (4.3 and 9.5%, respectively).
- The flexural strength values for all specimens fell within the range of 3.74 to 4.81 MPa. Mix SCC0 exhibited the lowest flexural strength, while SCC60 demonstrated the highest flexural strength. The result showed that the improvement rates of flexural strength were increased in specimens containing more iron slag as coarse aggregate. This can be related to the high hardness of slag grains that plays a significant role in augmenting the flexural strength.
- The presence of iron slag particles has resulted in a decrease in the water absorption (sorptivity) of concrete compared to concrete made with natural aggregates. The decreasing trend in water absorption has

been observed up to 30 percent replacement at 0.5 hours. However, at 1, 5, and 24 hours, the decreasing trend in water absorption occurred up to 40 percent replacement.

- The weight loss values for concrete mixtures containing 0%, 10%, 20%, 30%, 40%, 50%, and 60% iron slag are 1.73%, 0.83%, 0.59%, 1.05%, 1.41%, 1.88%, and 2.31%, respectively. As observed, the weight loss in samples containing 50% and 60% slag is higher than control concrete. However, the weight loss in samples containing 10%, 20%, 30% and 40% slag is lower than control concrete.
- SEM images showed, voids and porous structures are observed in the mix SCC0, which can affect its strength and durability. However, in the SCC20 design, a highly cohesive and uniform concrete surface is observed compared to the control sample. Moreover, in the SCC60 design, the amount of voids and porosity increases, leading to a decrease in concrete specimen strength and durability.

7 Future research plan

1. Evaluation of the thermal resistance of SCC specimens containing iron slag as a coarse aggregate.
2. Investigation of the acid resistance of SCC specimens containing iron slag as a coarse aggregate.
3. Utilizing higher percentage of iron slag as a coarse aggregate in SCC mixes.

References

[1] Rehman, S., Iqbal, S., Ali, A. "Combined influence of glass powder and granular steel slag on fresh and mechanical properties of self-compacting concrete", Construction and Building Materials, 178, pp. 153–160, 2018. https://doi.org/10.1016/j.conbuildmat.2018.05.148

[2] Okamura, H., Ouchi, M. "Self-compacting concrete", Journal of Advanced Concrete Technology, 1(1), pp. 5–15, 2003. https://doi.org/10.3151/jact.1.5

[3] Sheen, Y.-N., Wang, H.-Y., Sun, T.-H. "Properties of green concrete containing stainless steel oxidizing slag resource materials", Construction and Building Materials, 50, pp. 22–27, 2014. https://doi.org/10.1016/j.conbuildmat.2013.09.017

[4] Mohit, M., Haftbaradaran, H., Riahi, H. T. "Investigating the ternary cement containing Portland cement, ceramic waste powder, and limestone", Construction and Building Materials, 369, 130596, 2023. https://doi.org/10.1016/j.conbuildmat.2023.130596

[5] Chandru, P., Natarajan, C., Karthikeyan, J. "Influence of sustainable materials in strength and durability of self-compacting concrete: a review", Journal of Building Pathology and Rehabilitation, 3, Article 8, 2018. https://doi.org/10.1007/s41024-018-0037-1

[6] Dehane, S., Kriker, A., Salhi, A. "Influence of Saline-treated Wastewater on Properties of Concrete: An Experimental Study", Periodica Polytechnica Civil Engineering, 67(3), pp. 695–705, 2023. https://doi.org/10.3311/PPci.21841

[7] Pan, Z., Zhou, J., Jiang, X., Xu, Y., Jin, R., ..., Chen, W. "Investigating the effects of steel slag powder on the properties of self-compacting concrete with recycled aggregates", Construction and Building Materials, 200, pp. 570–577, 2019. https://doi.org/10.1016/j.conbuildmat.2018.12.150

[8] Singh, N., Singh, T., Kumar, M., Singh, A., Kumar, P. "Investigating the fresh state performance of concrete containing iron slag and recycled concrete aggregates", Materials Today: Proceedings, 65, pp. 1467–1477, 2022. https://doi.org/10.1016/j.matpr.2022.04.462

[9] Shajahan, S., Balakrishna, P. "Study on Properties of Self Compacting Concrete with Glass Powder and Steel Slag", International Journal of Trend in Scientific Research and Development, 4(1), pp. 267–270, 2019.

[10] Singh, G., Siddique, R. "Effect of iron slag as partial replacement of fine aggregates on the durability characteristics of self-compacting concrete", Construction and Building Materials, 128, pp. 88–95, 2016. https://doi.org/10.1016/j.conbuildmat.2016.10.074

[11] Sosa, I., Thomas, C., Polanco, J. A., Setién, J., Sainz-Aja, J. A., Tamayo, P. "Durability of high-performance self-compacted concrete using electric arc furnace slag aggregate and cupola slag powder", Cement and Concrete Composites, 127, 104399, 2022. https://doi.org/10.1016/j.cemconcomp.2021.104399

[12] Hussein, M. I. M., Rasheed, M. M. "Effect of Replacement of Fine and Coarse Aggregate by Iron Slag and Steel Slag on Concrete Properties", Eurasian Journal of Engineering and Technology, 15, pp. 90–103, 2023.

[13] Ibrahim, A. M., Mohamed, A. R., El-Khatib, A. M., Alabsy, M. T., Elsalamawy, M. "Effect of hematite and iron slag as aggregate replacement on thermal, mechanical, and gamma-radiation shielding properties of concrete", Construction and Building Materials, 310, 125225, 2021. https://doi.org/10.1016/j.conbuildmat.2021.125225

[14] Baalamurugan, J., Kumar, V. G., Chandrasekaran, S., Balasundar, S., Venkatraman, B., Padmapriya, R., Bupesh Raja, V. K. "Recycling of steel slag aggregates for the development of high density concrete: Alternative & environment-friendly radiation shielding composite", Composites Part B: Engineering, 216, 108885, 2021. https://doi.org/10.1016/j.compositesb.2021.108885

[15] Teymouri, E., Wong, K. S., Mohd Pauzi, N. N. "Iron slag pervious concrete for reducing urban runoff contamination", Journal of Building Engineering, 70, 106221, 2023. https://doi.org/10.1016/j.jobe.2023.106221

[16] Vijayaraghavan, J., Jude, A. B., Thivya, J. "Effect of copper slag, iron slag and recycled concrete aggregate on the mechanical properties of concrete", Resources Policy, 53, pp. 219–225, 2017. https://doi.org/10.1016/j.resourpol.2017.06.012

[17] Singh, G., Siddique, R. "Strength properties and micro-structural analysis of self-compacting concrete made with iron slag as partial replacement of fine aggregates", Construction and Building Materials, 127, pp. 144–152, 2016. https://doi.org/10.1016/j.conbuildmat.2016.09.154

[18] Díaz, M. F. M., Pabón, J.A. V., Martínez, S. R., Orduz, L. E. Z. "Iron slag as fine aggregate replacement and nanosilica particles in self-compacting concrete mixtures", Journal of Physics: Conference Series, 1386, 012032, 2019. https://doi.org/10.1088/1742-6596/1386/1/012032

[19] Kumar, A., Singh, N. "Mechanical performance of steel and iron slag concretes: A brief review", Materials Today: Proceedings, 2023. https://doi.org/10.1016/j.matpr.2023.06.463

[20] ASTM "ASTM C150/C150M-16e1 Standard Specification for Portland Cement", ASTM International, West Conshohocken, PA, USA, 2016. https://doi.org/10.1520/C0150_C0150M-16E01

[21] ASTM "ASTM C29/C29M-09 Standard test method for bulk density ("Unit Weight") and voids in aggregate", ASTM International, West Conshohocken, PA, USA, 2009. https://doi.org/10.1520/C0029_C0029M-23

[22] ASTM "ASTM C127-07 Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate", ASTM International, West Conshohocken, PA, USA, 2007. https://doi.org/10.1520/C0127-07

[23] ASTM "ASTM C128-07, Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate", ASTM International, West Conshohocken, PA, USA, 2007. https://doi.org/10.1520/C0128-07

[24] ASTM "C494/C494M-05 Standard Specification for Chemical Admixtures for Concrete", ASTM International, West Conshohocken, PA, USA, 2005. https://doi.org/10.1520/C0494_C0494M-05

[25] EFNARC "European Guidelines for Self-Compacting Concrete: Specification, Production and Use", Self-compacting Concrete European Project Group, Rep. SCC 028, 2005.

[26] BSI "Testing Concrete: Method for Determination of Compressive Strength of Concrete Cubes", British Standard Institution, London, UK, 1983.

[27] ASTM "ASTM C496/C496M-04 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", ASTM International, West Conshohocken, PA, USA, 2004. https://doi.org/10.1520/C0496_C0496M-04

[28] ASTM "ASTM C78-02 Standard Test Method for Flexural Strength of Concrete (Using Simple - Beam with Third –Point Loading)", ASTM International, West Conshohocken, PA, USA, 2004. https://doi.org/10.1520/C0078-02

[29] BSI "Method for determination of water absorption", British Standard Institution, London, UK,1983.

[30] ASTM "ASTM C597-09 Standard test method for pulse velocity through concrete", ASTM International, West Conshohocken, PA, USA, 2009. https://doi.org/10.1520/C0597-09

[31] Hall, C. "Water sorptivity of mortars and concretes: a review", Magazine of Concrete Research, 41(147), pp. 51–61, 1989. https://doi.org/10.1680/macr.1989.41.147.51

[32] Kannan, V., Ganesan, K. "Chloride and chemical resistance of self compacting concrete containing rice husk ash and metakaolin", Construction and Building Materials, 51, pp. 225–234, 2014. https://doi.org/10.1016/j.conbuildmat.2013.10.050

[33] Mendes, S. E. S., Oliveira, R. L. N., Cremonez, C., Pereira, E., Pereira, E., Medeiros-Junior, R. A. "Electrical resistivity as a durability parameter for concrete design: Experimental data versus estimation by mathematical model", Construction and Building Materials, 192, pp. 610–620, 2018. https://doi.org/10.1016/j.conbuildmat.2018.10.145

[34] EFNARC "Guidelines for Self-Compacting Concrete", 2002.

[35] Biskri, Y., Achoura, D., Chelghoum, N., Mouret, M. "Mechanical and durability characteristics of High Performance Concrete containing steel slag and crystalized slag as aggregates", Construction and Building Materials, 150, pp. 167–178, 2017. https://doi.org/10.1016/j.conbuildmat.2017.05.083

[36] Sharifi, Y., Afshoon, I., Asad-Abadi, S., Aslani, F. "Environmental protection by using waste copper slag as a coarse aggregate in self-compacting concrete", Journal of Environmental Management, 271, 111013, 2020. https://doi.org/10.1016/j.jenvman.2020.111013

[37] Guo, Y., Xie, J., Zheng, W., Li, J. "Effects of steel slag as fine aggregate on static and impact behaviours of concrete", Construction and Building Materials, 192, pp. 194–201, 2018. https://doi.org/10.1016/j.conbuildmat.2018.10.129

[38] Palankar, N., Ravi Shankar, A. U., Mithun, B. M. "Durability studies on eco-friendly concrete mixes incorporating steel slag as coarse aggregates", Journal of Cleaner Production, 129, pp. 437–448, 2016. https://doi.org/10.1016/j.jclepro.2016.04.033

[39] Forster, S. W. "Chapter 31: Soundness, Deleterious Substances, and Coatings", In: STP169D-EB Significance of tests and properties of concrete and concrete making materials, , ASTM International, West Conshohocken, PA, USA, 2006. https://doi.org/10.1520/STP169D-EB

[40] Khanzadi, M., Behnood, A. "Mechanical properties of high-strength concrete incorporating copper slag as coarse aggregate", Construction and Building Materials, 23(6), pp. 2183–2188, 2009. https://doi.org/10.1016/j.conbuildmat.2008.12.005

[41] Wu, W., Zhang, W., Ma, G. "Optimum content of copper slag as a fine aggregate in high strength concrete", Materials & Design, 31(6), pp. 2878–2883, 2010. https://doi.org/10.1016/j.matdes.2009.12.037

[42] Sharma, R., Khan, R. A. "Sustainable use of copper slag in self compacting concrete containing supplementary cementitious materials", Journal of Cleaner Production, 151, pp. 179–192, 2017. https://doi.org/10.1016/j.jclepro.2017.03.031

[43] Lori, A. R., Hassani, A., Sedghi, R. "Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate", Construction and Building Materials, 197, pp. 130–142, 2019. https://doi.org/10.1016/j.conbuildmat.2018.11.230

[44] Teymouri, E., Wong, K. S., Tan, Y. Y., Pauzi, N. N. M. "Mechanical behaviour of adsorbent pervious concrete using iron slag and zeolite as coarse aggregates", Construction and Building Materials, 388, 131720, 2023.

[45] Behnood, A., Gharehveran, M. M., Asl, F. G., Ameri, M. "Effects of copper slag and recycled concrete aggregate on the properties of CIR mixes with bitumen emulsion, rice husk ash, Portland cement and fly ash", Construction and Building Materials, 96, pp. 172–180, 2015. https://doi.org/10.1016/j.conbuildmat.2015.08.021

[46] Al-Jabri, K. S., Al-Saidy, A. H., Taha, R. "Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete", Construction and Building Materials, 25(2), pp. 933–938, 2011. https://doi.org/10.1016/j.conbuildmat.2010.06.090

[47] Al-Jabri, K. S., Hisada, M., Al-Saidy, A. H., Al-Oraimi, S. K. "Performance of high strength concrete made with copper slag as a fine aggregate", Construction and Building Materials, 23(6), pp. 2132–2140, 2009. https://doi.org/10.1016/j.conbuildmat.2008.12.013

[48] Sheikh, E., Mousavi, S. R., Afshoon, I. "Producing green Roller Compacted Concrete (RCC) using fine copper slag aggregates", Journal of Cleaner Production, 368, 133005, 2022. https://doi.org/10.1016/j.jclepro.2022.133005

[49] Brand, A. S., Roesler, J. R. "Interfacial transition zone of cement composites with steel furnace slag aggregates", Cement and Concrete Composites, 86, pp. 117–129, 2018. https://doi.org/10.1016/j.cemconcomp.2017.11.012

[50] Afshoon, I., Miri, M., Mousavi, S. R. "Comprehensive experimental and numerical modeling of strength parameters of eco-friendly steel fiber reinforced SCC containing coarse copper slag aggregates", Construction and Building Materials, 367, 130304, 2023. https://doi.org/10.1016/j.conbuildmat.2023.130304