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RESEARCH PAPER

Mechanical and Durability Properties of Green SCC Mixed with Pozzolan and Ferro-Silicomanganese Slag as Partial Aggregate Replacement

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ABSTRACT: Making green Self-Compacting Concrete (SCC) is one of the valuable measures that, along with the development of communities, helps to reduce environmental pollution. 10 different SCC mix designs were designed and fabricated using Khash and Sirjan pozzolans, 25, 50, 75, and 100% replacement of aggregate with dimensions in the range of 4.75-9.5 mm with Ferro-Silicomanganese Slag (FSiMnS). The water-to-cement ratio is 0.36 for all SCC mixes. Slump flow, V-funnel, and l-box tests were performed on fresh concrete to investigate the fresh properties and rheology of green SCC. A total of 250 cubic specimens of 10 × 10 cm^2, 60 cubic specimens of 15 × 15 cm^2, and 40 cylindrical specimens of 10 × 20 cm^2 for testing compressive strength, Rapid Chloride Permeability Test (RCPT), surface electrical resistance, water penetration depth under pressure, and half-hour water absorption to evaluate the durability properties of concrete, were sampled. From the obtained results, it was concluded that replacing the aggregate with FSiMnS provides better compressive strength results up to 18%, and somehow increase in durability test results, but has adverse effects on the workability parameters of SCC. Sirjan pozzolan has shown better performance than Khash pozzolan in all durability tests, while Khash pozzolan has higher initial compressive strength.

Keywords: Ferro-Silicomanganese Slag, Green SCC, Workability Tests, Durability Tests, Pozzolan.

1. Introduction

Developments in science and technology in the last decades have expanded various industries. As a result, there is an increased need for materials such as iron, steel, copper, and concrete (Afshoon and Sharifi, 2020; Sharifi, 2012; Sharifi et al., 2013 and 2020). Concrete is one of the most important structural materials in the world, which is used in marine and aquatic environments due to its reliability and cost-effectiveness. However, in some cases, due to poor design, poor execution, poor quality of materials, and environmental conditions not included in the design or a combination of these factors, the reinforced concrete structure will not have the desired

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performance and permanence during its useful life. Nowadays, resource sustainability and efficiency in the manufacturing industry have become widely important issues, and the change of attitudes toward secondary materials strengthens this idea that pozzolans like the foundry slag can be used as concrete aggregates (Amran et al., 2021; Guo et al., 2020; Mohamed and Najm, 2017; Mohan and Mini, 2018; Santamaría et al., 2017).

Aggregate, along with cement and water, is one of the most important components of concrete, as it occupies a volume of about 55% to 80% of concrete. The rapid increase in the consumption of natural aggregates, due to the increase in the construction industry in the world, means that aggregate reservoirs, especially in desert areas, are rapidly declining. It has been reported that without suitable permanent aggregates for using in the near future, the concrete industry as a whole will consume 8 to 12 billion tons of aggregates. Such excessive consumption of natural aggregates leads to environmental degradation. Therefore, it is necessary to find a permanent alternative aggregate instead of a natural one for concrete construction and exploit it by examining the possibility of using industrial waste and ancillary materials. This will lead to the design of sustainable concrete and a green environment (Marinković et al., 2010; Rahat Dahmardeh et al., 2021).

The mass production of cement and the supply of aggregates and raw materials for making concrete from rivers and mines have left negative effects on the face of nature and the environment, which is expanding every day. In order to deal with these destructive effects, extensive research has been done, which often seeks to replace cement and other concrete constituents with other materials. The use of industrial waste for this purpose, in addition to satisfying the above purpose, causes the reuse of these materials, too (Jindal et al., 2023; Karakurt and Dumangöz, 2022; Marinković et al., 2010; Sharifi et al., 2020). Slag occupies a large part of the factory plant space, which can cause several environmental problems, including dust in urban areas and reduced available space. The slag use has been very limited so far. These include the use as rubble in the road and railway infrastructure and the construction of airfields, firebricks, etc.

Today, researchers in the concrete world seek to increase the strength and durability of concrete with respect to environmental aspects. The production of large quantities of slag from the ferroalloy industry and the destructive impact of these materials on humans and the environment are worrying. Conventional concreting requires sufficient compaction to ensure the characteristic strength and durability of concrete, while a lack of proper compaction of conventional concrete leads to air cavities, reduced strength, reduced durability, and a negative impact on other physical and chemical properties of concrete (Buruiana et al., 2022; Dey et al., 2022; Gencel et al., 2021). Self-Compacting Concrete (SCC) is used in heavy and high-level structures that need sufficient durability against uncertain natural conditions. SCC flows by its own weight due to gravity and does not need vibration to achieve compaction. The use of superplasticizers in SCC is necessary in order to achieve proper flow, and adding a large amount of powder and viscosity modifiers prevents segregation of SCC.

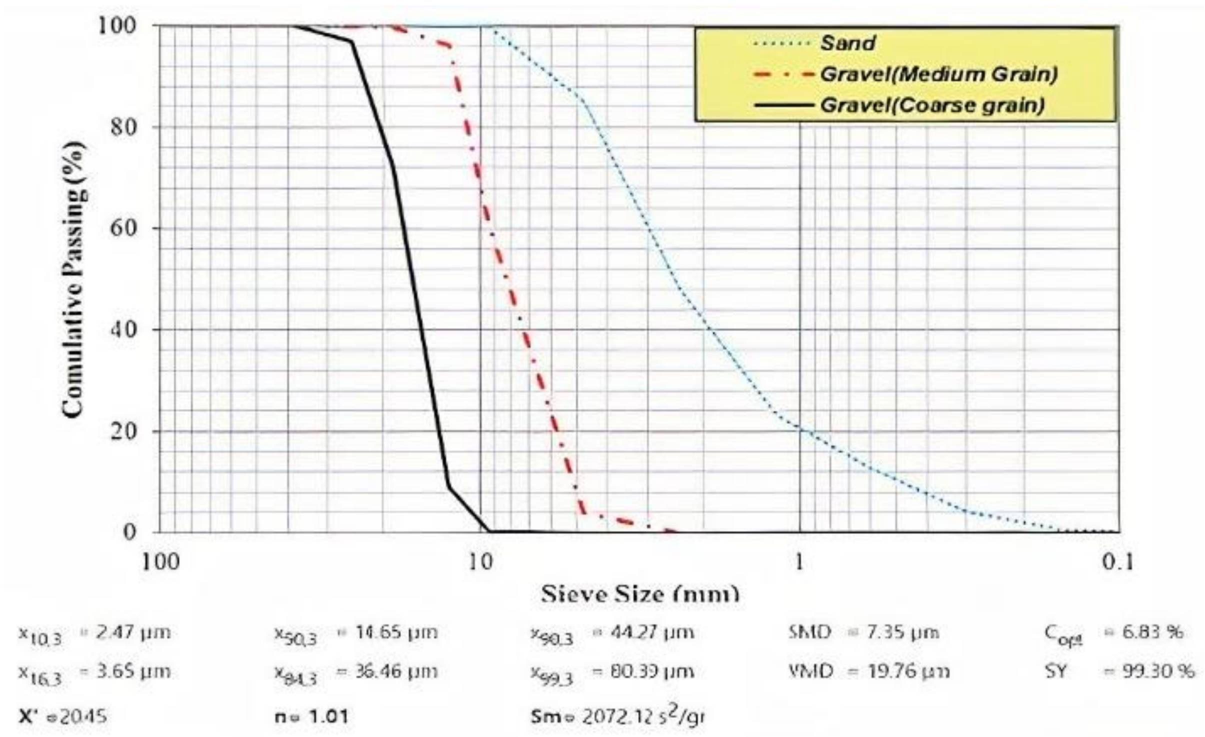
High advantages of concreting, reduction of construction time, no need for vibrators, good flow ability in sections with high reinforcement density, reduction of noise pollution, better-finished surface, higher strength, and durability are among the advantages of SCC (Gupta and Siddique, 2020; Siddique, 2019; Yön et al., 2024). The advantages of using various types of slags and other by-products in SCC, has made researchers all over the world to conduct extensive studies in this domain (Amran et al., 2021). Ferro-Silicomanganese Slag (FSiMnS) is a ferrous industrial by-product consisting of the ferrosilica manufacturing industry. FSiMnS is a by-product of alloy steel production (Nath et al., 2022). Depending on the process of solidification, the slag is available in crystalline hard stone and granulated glassy form. The second one is more reactive due to the presence of amorphous phases.

Therefore, granulated slag has been mostly used as a supplementary cementitious material, either blending with clinker or as a precursor for alkali-activated binder. Whereas the first is less reactive and has been mostly used as an aggregate, which can enhance the properties of the concrete (Tamayo et al., 2023). The internal composition of FSiMnS facilitates its grounding compared to other metal slags. In addition, granular FSiMnS has a higher specific surface compared to other massive silicon-manganese slags (Luo et al., 2022).

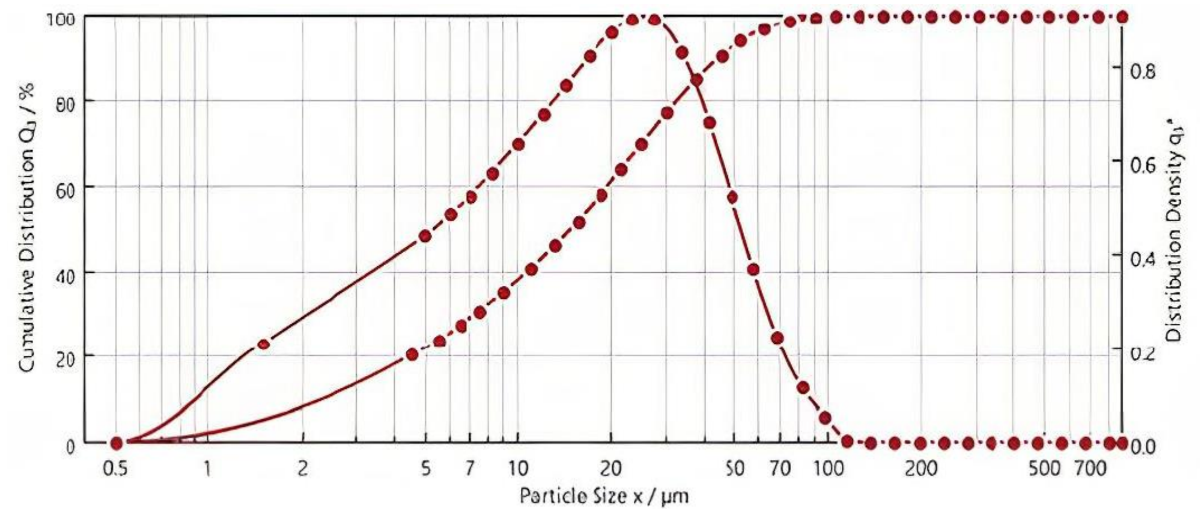
In this study, in order to simultaneously improve the compressive strength and durability of SCC, considering the reduction of environmental pollution caused by the accumulation of FSiMnS wastes, they were used as a replacement for pea aggregate. Although FSiMnS has been used as aggregate in conventional concrete, the simultaneous use of both natural pozzolans and FSiMnS to investigate both the compressive strength and durability of SCC has not been reported yet.

2. Material Properties

In this research, river sand (fine aggregate) with a maximum size of 4.75 mm, a specific gravity of 2.65 g/cm^3, water absorption of 2%, fineness modulus of 3.15, and natural crushed aggregate (coarse aggregates) with a maximum size of 19 mm, specific gravity 2.7 g/cm^3, water absorption of 1% (Figure 1a), Portland cement Type 2 (according to ASTM C150 (ASTM International, 2024) and ISIRI 389 (ISIRI, 2025)) with a specific gravity of 3.15 g/cm^3, initial setting time of 125 min, and final setting time of 180 min which was produced in Kerman cement industries group, were used. The physical characteristics/granulation distribution of cement and chemical properties of cement are shown in Figure 1b and Table 1, respectively.



(a)



(b)

Fig. 1. a) Particle size distribution of aggregate; and b) Particle size distribution of Type 2 cement used in the project

Likewise, two types of pozzolans, whose specifications are presented in Table 2, and P10-3R polycarboxylate superplasticizer manufactured by a construction chemical company have been used. In this research, 4.75 mm size green FSiMnS aggregate passed through a sieve (9.5 mm size remained) has been used to make green (slag) SCC (Figure 2). Water absorption and specific gravity test according to ASTM C127 (ASTM International, 2025a) were performed on these aggregates. These aggregates have a water absorption of 0.6% and a density of 3 tons/m^3.

3. Mixing Design and Test Method

3.1. Mixing Design

In order to gain comprehensive knowledge about the performance of FSiMn and to investigate the fresh and hardened properties of SCC, five mixing design of SCC with Khash pozzolan (Designs 1-5), and five mixing designs with Sirjan pozzolan (Designs 6-10), respectively by replacing 25, 50, 75, and 100% of (pea) aggregate, sized 4.75-9.5 mm, compared to the control sample was made. Details of the mixing design and replacement ratios are provided in Table 3.

Table 1. Chemical analysis of Type 2 cement

Component	L.O.I	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	C_3S	C_2S	C_3A	C_4AF
Result	1.3	21.03	4.85	3.92	63.34	1.7	2.52	51.7	21.3	6.2	11.2

Table 2. Chemical analysis of pozzolan

Component	L.O.I	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl
Khash pozzolan	1.97	59.18	18.06	5.6	7.28	2.00	0.25	3.79	1.85	0.014
Sirjan pozzolan	4.53	62.22	17.82	3.84	6.16	0.80	0.02	2.84	2.12	0.009

Fig. 2. Ferro-silicomanganese slag of ferroalloy industries

3.2. Workability Tests

A SCC slump-flow test according to ASTM C1611 was performed on 10 mixing designs to determine the performance and flow of concrete (Figure 3). The results are presented in Table 4. The l-box test is another test for measuring the permeability of SCC, which has been performed according to EN 12350-10 (European Committee for Standardization, 2011). The withdrawal time of concrete from EN 12350-9 standard (British Standards Institution, 2010) is measured and is used as a criterion for determining the filling ability and viscosity of the concrete paste. The results of these experiments are listed in Table 4.

4. Hardened Concrete Tests

4.1. Compressive Strength Test

From each mixing plan, 25 cubic samples (10 × 10 cm^2), 6 cubic samples (15 × 15 cm^2), and 4 cylindrical samples (10 × 20 cm^2) have been made for resistance and durability tests. Then, the samples were stored in a water pool according to ASTM C192 (ASTM International, 2025b) until the desired age of each test. Cube concrete samples at the ages of 7, 28, and 90 days are broken by the compressive strength jack, and the results are presented in Table 5.

Table 3. The mixing design and replacement ratios

Plan No.	Cement (kg)	Khash pozzolan (kg)	Sirjan pozzolan (kg)	Coarse aggregate (9.5-19) (mm)	Fine aggregates (4.75-9.5) (mm)	Ferro-silicomanganese aggregate (4.75-9.5) (mm)	Sand (kg)	Water (kg)	Super plasticizer (gr)	w/cm
1	380	150	0	312	312	0	1050	198	60	0.37
2	380	150	0	312	234	78	1050	198	60	0.37
3	380	150	0	312	156	156	1050	198	60	0.37
4	380	150	0	312	78	234	1050	198	60	0.37
5	380	150	0	312	0	312	1050	198	60	0.37
6	380	0	150	312	312	0	1050	198	60	0.37
7	380	0	150	312	234	78	1050	198	60	0.37
8	380	0	150	312	156	156	1050	198	60	0.37
9	380	0	150	312	78	234	1050	198	60	0.37
10	380	0	150	312	0	312	1050	198	60	0.37

Fig. 3. SCC slump-flow test

Table 4. SCC workability tests

Workability test	SCC1	SCC2 25%R	SCC3 50%R	SCC4 75%R	SCC5 100%R	SCC6	SCC7 25%R	SCC8 50%R	SCC9 75%R	SCC10 100%R
Slump flow	750 mm	740 mm	720 mm	720 mm	700 mm	700 mm	680 mm	660 mm	650 mm	650 mm
T50 cm	3 s	3.2 s	4 s	4.5 s	5 s	3.5 s	4 s	4 s	4.3s	4.5 s
L-box	1	0.98	0.96	0.95	0.9	0.98	0.94	0.92	0.8	0.78
V-funnel	8 s	8.2 s	8.5 s	9 s	10 s	9 s	9.6 s	10 s	10.4 s	11s

Table 5. Compressive strength test of concrete

Plan number	Compressive strength (MPa)											
	7 days				28 days				90 days			
	S1	**S2**	**S3**	**Mean value**	**S1**	**S2**	**S3**	**Mean value**	**S1**	**S2**	**S3**	**Mean value**
1	38.1	37.7	37.6	37.8	51.4	47.1	45.7	48	58	52.2	55.3	55.2
2	38.4	37.6	38.7	38.2	50.9	55.9	50.5	52.4	57.8	62.3	58.8	59.6
3	34.2	36.1	34.5	34.9	53.4	51.6	51.1	52	64.7	60.7	54.8	60.1
4	39.3	38.4	38.2	38.6	53.4	57.7	48.8	53.3	60.9	60	65.7	62.2
5	39.8	43.1	41.8	41.6	55.6	56.6	56.5	56.2	67.1	69	67.6	67.9
6	30.2	30.4	29.6	30.1	42.1	38.9	38.7	39.9	57.3	57.7	51.7	55.6
7	32.7	32.7	32.4	32.6	44.7	44.4	43.1	44.1	56	58.2	57.5	57.2
8	33.5	32.5	34.6	33.5	45.3	45	41.2	43.8	56.9	58.4	62.4	59.2
9	36.8	35.9	33.9	35.5	42.6	42.6	47.9	44.1	62	57.5	60.9	60.1
10	36.8	34.5	35.5	35.6	49.4	49.7	49	49.4	65.1	62.1	60.8	62.7

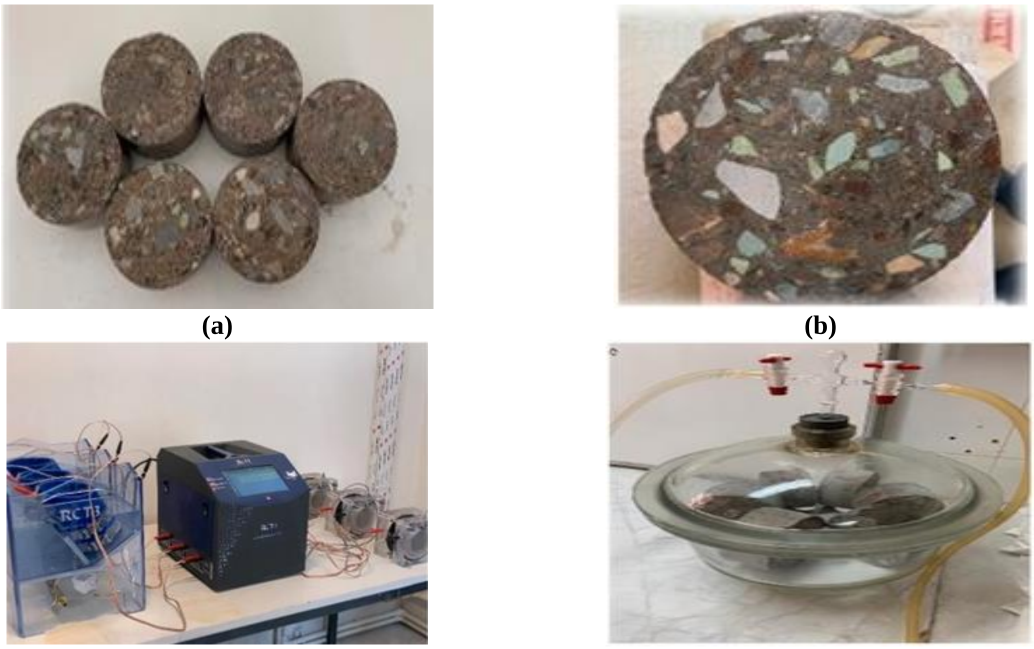
4.2. Rapid Chloride Permeability Test (RCPT)

The RCPT is one of the valid tests of concrete durability. Cylindrical specimens were stored in curing ponds for 90 days, and according to ASTM C1202 (ASTM International, 2025c) were cut into three pieces with a thickness of 5 cm (Figures 4a and 4b). The sliced tablet was placed in a vacuum situation for 3 hours and a saturated situation for 18 hours, after which it was placed inside the RCPT cell for testing.

Solutions of NaCl 3% and NaOH 0.3 M are poured on both sides of the cell as shown in Figures 4c and 4d. A potential difference of 60 volts was applied to both ends of the sample for 6 hours, the current and charge passing for each of the tests in this interval were controlled and recorded. According to ASTM C1202 (ASTM International, 2025c), the charge per unit of columbus indicates the resistance of the concrete to the penetration of chloride ions (Table 6).

4.3. Depth of Water Penetration under Pressure Test

Firstly, the bottom surface of the concrete sample 15 × 15 cm is brushed, then the test-piece is subjected to 500 kPa pressure (5 Bar) from the bottom surface for three days (Figure 5a), the test-piece is divided into two halves by a compressive strength jack and the maximum water penetration depth which is a parameter for evaluating water penetration in concrete have been achieved. The results are shown in Figure 5b.



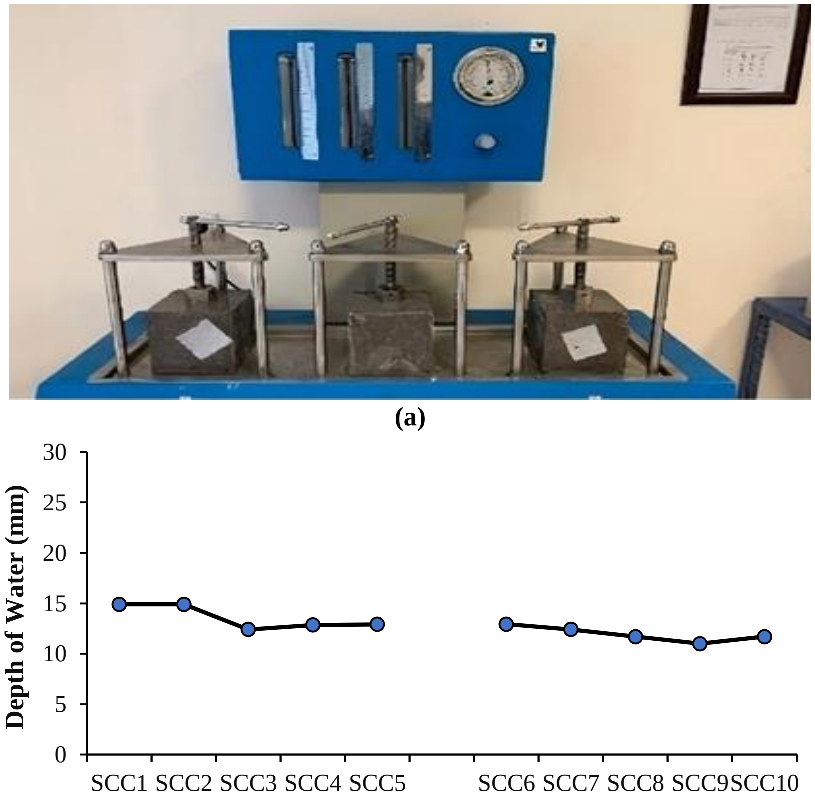
(a) (b) (c) (d)

Fig. 4. a, b) Cutting cylindrical concrete samples; and c, d) Preparation of cut sections for RCPT test

Table 6. The rapid chloride permeability test

Mix design number	Flux (coulomb) S1	S2	S3	Mean value	*COV(%)	Chlorine ion penetration rate
1	2802	2776	2854	2810	0.9993%	Moderate
2	2934	2829	2748	2837	2.3244%	Moderate
3	2729	2368	2567	2554	5.0051%	Moderate
4	2129	2200	2435	2254	5.0232%	Moderate
5	2403	2114	2112	2209	5.3584%	Moderate
6	2103	2247	2143	2164	2.4286%	Moderate
7	2212	1977	2007	2065	4.3791%	Moderate
8	1870	1987	1997	1951	2.559%	Low
9	2177	1879	1790	1948	7.3555%	Low
10	1777	1401	1687	1621	8.5616%	Low

* **COV**: Coefficient of Variations



(b)

Fig. 5. a) Depth of water penetration under pressure test; and b) Depth of water penetration under pressure results

Due to the replacement of FSiMnS at the level of (pea) aggregate in concrete, the changes in water penetration depth under pressure are negligible, and the results obtained from this test on slag concrete are almost equal to the control sample without slag.

4.4. Four-Point Electrical Resistance Test

Electrical strength, as one of the characteristics of concrete, indicates some of its important properties, such as permeability, as well as the absorption of water. The electrical resistance of concrete, especially in corrosive areas with high penetration of chloride ions such as the Persian Gulf, means that the higher the electrical resistance, the lower the permeability. Cylindrical samples were tested after 90 days of curing in order to standard conditions, and then the device is placed on the surface of the concrete sample, and the strength of the sample is determined to a certain depth.

The concrete sample is marked at 0, 90, 180, and 270 degrees' direction before the test. The two internal electrodes of the device calculate the difference in electrical potential created, and the two external electrodes introduce alternating current to the concrete surface. In practice, the electrical resistance (R) is calculated directly by the device (Table 7).

4.5. Half-Hour Water Absorption Test

In the UK, the quality of concrete tables and some prefabricated parts are tested with a half-hour water absorption test. For example, the half-hour water absorption of a table should not exceed 2%. In short-term water absorption tests, there is sensitivity to the shape and size of the sample, and the surface-to-volume ratio is important. The BS 1881-122 standard (British Standards Institution, 2020) provides specific correction factors so that if the sample diameter and length change relative to the standard diameter and length, the corrected results can be calculated.

The samples made in the Kerman Cement Concrete Research Center have been tested. Obviously, the lower the water absorption percentage of the concrete sample is, the lower the porosity and permeability of the concrete will be. This indicates a better performance against the penetration of destructive ions by water into the concrete and better durability of the plan. The results of the half-hour water absorption test of the ten mixing designs are presented in Table 8.

Table 7. Four-point electrical resistance test

Mix design number	Test case	Electrical resistance (kΩ.cm)	Standard deviation	Relative standard deviation	Average electrical resistance	The level of chloride permeability according to the AASHTO T358
	A	18.75	1.11	5.91		
1	B	19.775	0.51	2.60	19.27	Moderate
	C	19.275	0.52	2.72		
	A	19.1	1.28	6.09		
2	B	18.9	0.50	2.19	19.07	Moderate
	C	19.2	1.02	5.00		
	A	19.4875	0.63	3.25		
3	B	19.9	0.28	1.68	19.90	Moderate
	C	20.3	0.81	4.43		
	A	19.5625	0.38	1.95		
4	B	19	0.88	4.63	19.53	Moderate
	C	20.0375	0.46	2.31		
	A	18.9125	0.76	4.04		
5	B	19.3125	0.65	3.35	19.11	Moderate
	C	19.1125	0.76	3.95		
	A	21.7625	0.69	3.17		
6	B	22.2125	0.81	3.65	22.75	Low
	C	24.2875	1.24	5.09		
	A	24.8375	0.73	2.92		
7	B	23.35	0.34	1.45	24.47	Low
	C	25.225	0.74	2.92		
	A	24.65	0.69	2.80		
8	B	27.1625	1.14	4.21	25.94	Low
	C	26	0.46	1.76		
	A	26.2	0.58	2.42		
9	B	25.8	0.52	2.18	26.53	Low
	C	27.6	0.81	3.50		
	A	28.45	0.56	1.96		
10	B	28.375	0.83	2.92	28.81	Low
	C	29.6125	1.23	4.16		

4.6. Electrical Conductivity Test

Electrical conductivity test of concrete measures the volumetric electrical conductivity of a saturated concrete sample to identify the resistance of concrete to penetration of chloride ions by diffusion. The term volumetric is used because electrical conductivity is measured by measuring the electric current in the entire body of a concrete sample. In this test, the current is measured one minute after the voltage was applied. The obtained current, applied voltage, and dimensions are used to calculate the volumetric electrical conductivity of concrete. According to research, a decrease in electrical conductivity indicates an increase in the durability of concrete (Table 9).

5. Discussion and Results

5.1. Rheological Properties of Fresh Concrete

As expected, the addition of Ferro-silicomanganese aggregates has led to changes in the properties of our fresh and hardened concrete. In this section, we review the test diagrams, details, and results obtained.

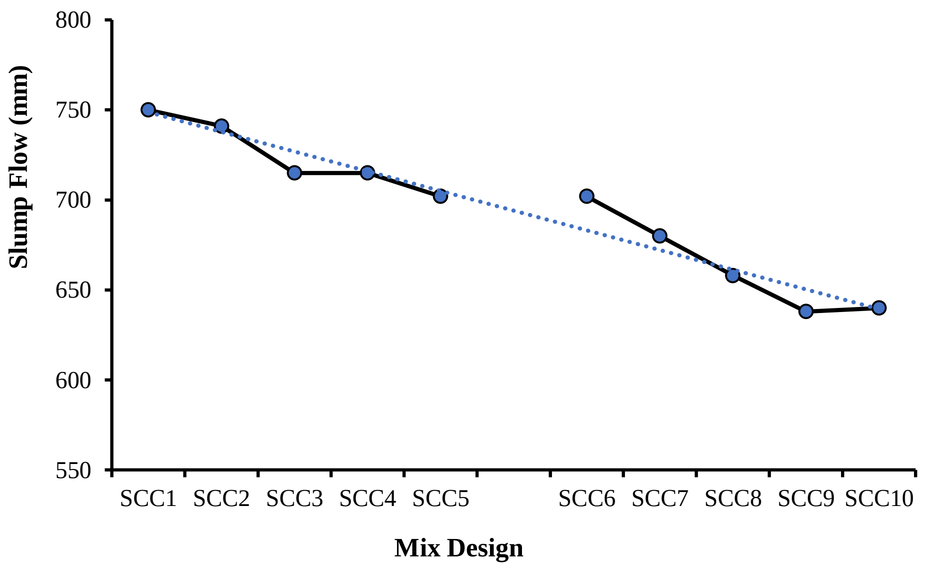
Table 8. Half-hour water absorption test

Mix design number	Test case code	Water absorption	Correction factor	Modified water absorption	Average water absorption
	A	1.763	1.30	2.29	
1	B	1.492	1.31	1.95	1.99
	C	1.320	1.31	1.72	
	A	1.580	1.31	2.07	
2	B	1.948	1.32	2.56	2.27
	C	1.665	1.31	2.18	
	A	2.588	1.31	3.38	
3	B	2.263	1.32	2.99	3.04
	C	2.082	1.32	2.76	
	A	2.148	1.32	2.83	
4	B	2.272	1.32	3.01	3.00
	C	2.415	1.32	3.18	
	A	2.207	1.31	2.89	
5	B	2.382	1.32	3.13	3.02
	C	2.302	1.31	3.02	
	A	2.512	1.32	3.33	
6	B	2.406	1.32	3.17	3.10
	C	2.131	1.32	2.80	
	A	2.226	1.32	2.93	
7	B	2.086	1.32	2.74	2.94
	C	2.394	1.32	3.15	
	A	2.065	1.31	2.71	
8	B	1.794	1.32	2.36	2.54
	C	1.937	1.32	2.55	
	A	1.911	1.32	2.51	
9	B	1.934	1.31	2.54	2.42
	C	1.683	1.31	2.21	
	A	1.630	1.32	2.14	
10	B	1.842	1.32	2.43	2.29
	C	1.737	1.32	2.29	

Table 9. Electrical conductivity test

Mix design number	Current (mA)	Voltage	Test case thickness (mm)	Diameter (mm)	Conversion factor (K)	Volumetric electrical conductivity (mS/m)	Average
1	103	60	50	99	1273.2	11.15	11.03
	100.7	60	50	99	1273.2	10.90	
2	101.6	60	50	99	1273.2	11.00	10.98
	101.3	60	50	99	1273.2	10.97	
3	98.2	60	50	99	1273.2	10.63	10.50
	95.7	60	50	99	1273.2	10.36	
4	94.4	60	50	99	1273.2	10.22	9.88
	88.2	60	50	99	1273.2	9.55	
5	75	60	50	99	1273.2	8.12	8.77
	87	60	50	99	1273.2	9.42	
6	81.3	60	50	99	1273.2	8.80	8.78
	80.9	60	50	99	1273.2	8.76	
7	75.9	60	50	99	1273.2	8.22	7.71
	66.5	60	50	99	1273.2	7.20	
8	64.7	60	50	99	1273.2	7.00	7.20
	68.3	60	50	99	1273.2	7.39	
9	67	60	50	99	1273.2	7.25	7.09
	64	60	50	99	1273.2	6.93	
10	74	60	50	99	1273.2	8.01	7.22
	59.3	60	50	99	1273.2	6.42	

According to Figure 6a, by adding the percentage of ferro-silicomanganese aggregate to the control design, which does not contain slag, the flow chart of SCC has shown a downward trend. Therefore, the replacement of slag from zero to one hundred percent, respectively, reduced the slump-flow in the first 5 designs (containing Khash pozzolan) from 750 mm to 700 mm, as well as in the second 5 designs (containing Sirjan pozzolan) from 700 to 650 mm. According to Figure 6b, the downward trend and decrease in the results obtained from the l-box test indicate a decrease in the permeability of SCC with increasing the replacement percentage of Ferro-silicomanganese aggregate.



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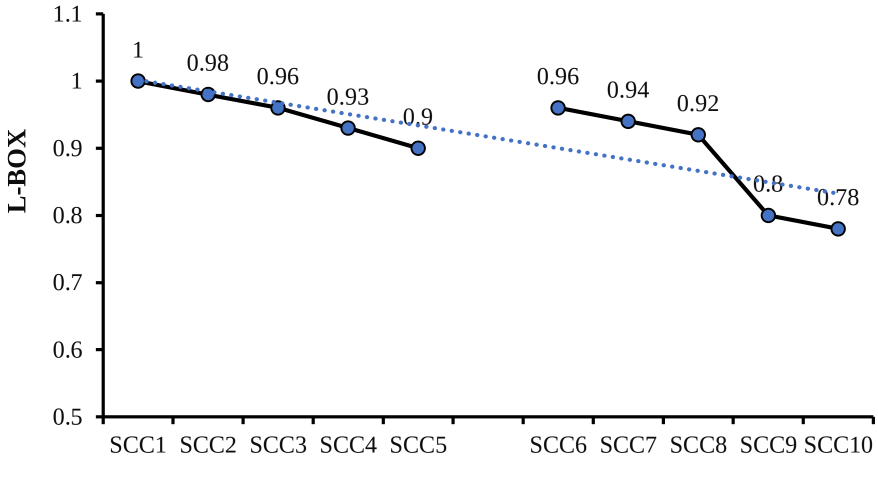

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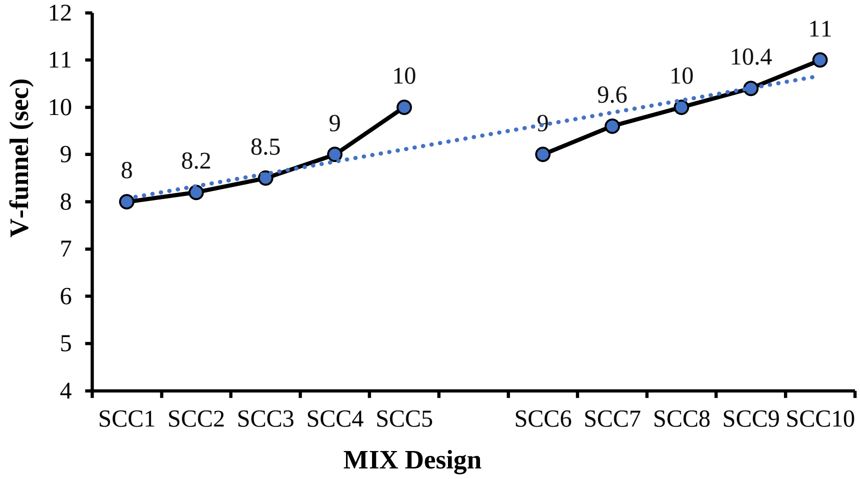

(c)

Fig. 6. a) SCC slump-flow test; b) The L box test; and c) V-funnel test on self-compacting concrete

As can be seen from this diagram, the height-to-end ratio of the l-box test has decreased from 1 to 0.9 in the first 5 designs and from 0.96 to 0.78 in the second 5 designs. The V-funnel test is performed to evaluate the filler ability of SCC.

According to the results (Figure 6c), by increasing the replacement of Ferro-silicomanganese aggregate in the first 5 designs, the discharge time of the funnel increased from 8 seconds to 10 seconds and in the second 5 designs from 9 seconds to 11 seconds, which indicates a decrease in the filling ability and a decrease in the efficiency of SCC compared to the control design.

5.2. Strength and Durability Properties of Concrete

As shown in Figure 7, the increase in the percentage of slag replacement in all mixing designs compared to the control designs has a significant increase in both strength and durability. Since in this study two different types of pozzolans have been used, the growth trend of strength is also examined. SCC containing Khash pozzolans (Design 1 to 5) at the age of 7, 28 and 90 days had a 10, 16 and 23% increase in strength compared to the control sample (Design 1), and SCC containing Sirjan pozzolan (design 6 to 10) at the ages of 7, 28 and 90 days had a19, 23, and 13% growth of resistance compared to the control sample (Design 6), respectively.

Compressive strength of concrete containing Khash pozzolans at the ages of 7 to 28, and 28 to 90 days, on average, increased by 37 and 16%, respectively, while the compressive strength of concrete containing Sirjan pozzolans at the ages of 7 to 28, and 28 to 90 days, increased by 32 and 33%, respectively. On average, the compressive strength of plans containing pozzolan Khash at the ages of 7, 28, and 90 days is 14%, 18%, and 3% higher than samples containing Sirjan pozzolans, respectively. Therefore, it can be concluded that due to the higher initial strength results of concrete containing Khash pozzolan, the slope of Sirjan pozzolan growth curve is higher, and this difference has reached 3% at the age of 90 days. RCPT is one of the most common tests of concrete durability. Figure 8a shows the process of reducing the charge passing through the concrete test containing slag. Reducing the charge through the concrete section indicates an increase in the durability and resistance of concrete against the penetration of chloride ions. The control design containing Khash pozzolan (SCC1) and the design (SCC5) containing FSiMn aggregate have passed 2810 and 2204 coulomb current, respectively. Therefore, the replacement of this aggregate has led to an improvement of at least 20% in durability.

Control design (SCC6) containing Sirjan pozzolan with 2164 coulombs has been in the medium permeability category, and design (SCC10) containing FSiMn aggregate with 1621 coulombs has been in the low permeability category. This reduction in flow rate indicates a 25% increase in green concrete durability rather than plain concrete. According to the results obtained from the four-point electrical resistance test, Figure 8b shows the trend of changes in the surface electrical resistance of the sample containing slag. The electrical resistance of the SCC1 design (control design containing Khash pozzolan) has not changed significantly compared to the SCC5 design (containing FSiMn aggregate) and is almost constant, but the electrical resistance of the SCC10 design (containing FSiMn aggregate) has increased by 26% compared to the SCC6 design (control plan containing Sirjan pozzolan).

According to the obtained results, Sirjan pozzolan shows higher electrical resistance in similar conditions than Khash pozzolan. A half-hour water absorption test is another criterion for measuring the durability of concrete. According to Iranian regulations, water absorption up to 2% is recommended for areas with high corrosion. The results obtained from experiments on 90 days tests indicate better performance of Sirjan pozzolan along with FSiMn aggregate than Khash pozzolan. The half-hour water absorption rate of the control design containing Khash pozzolan (SCC1) and the design (SCC5) containing FSiMn aggregate is 1.191 and 1.807%, respectively. While the half-hour water absorption of the control design containing Sirjan pozzolan (SCC6) and the design containing FSiMn aggregate is equal to 1.861 and 1.375%, respectively. The results obtained from all designs are within the standard range, so the produced green concrete can be applied in areas with high corrosion (Figure 9a).

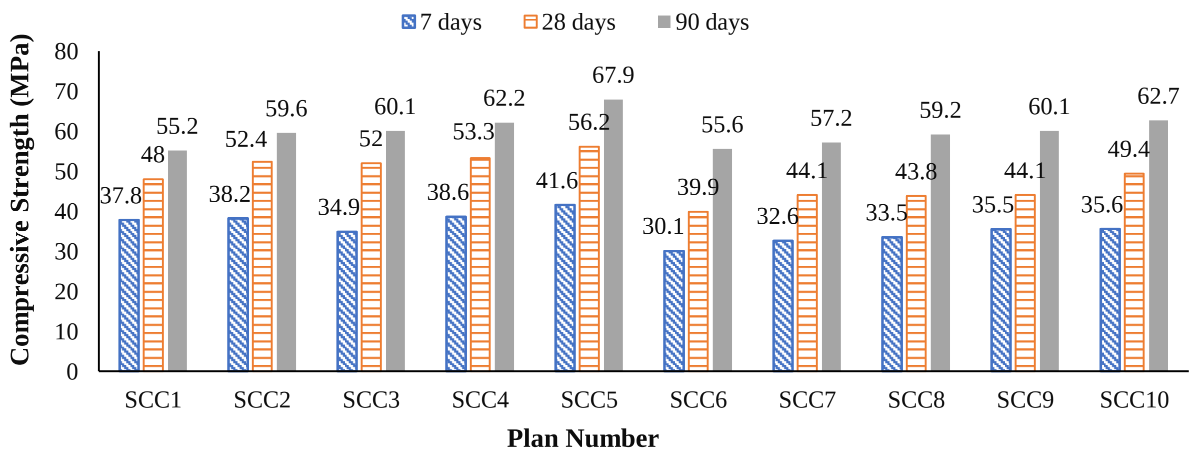

Fig. 7. Compressive strength 7, 28, and 90 days of SCC

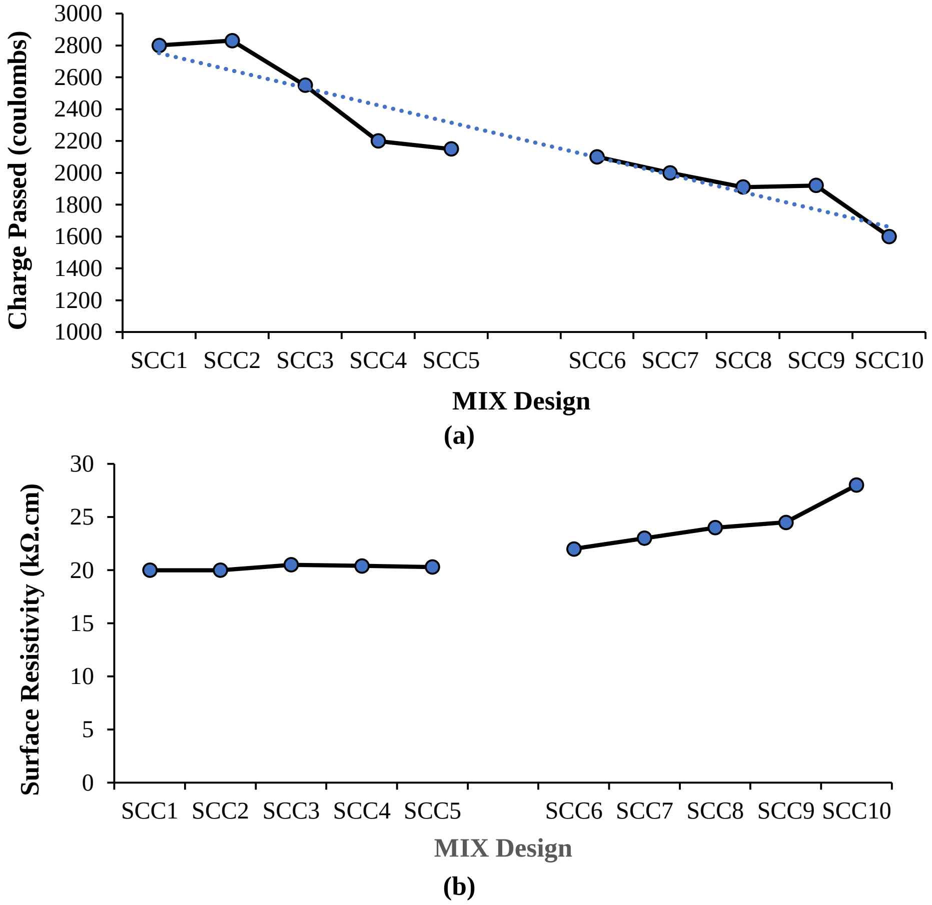

Fig. 8. a) RCPT at the age of 90 days; and b) Four-point Electrical Resistance Test (ESRT) at the age of 90 days

According to the results of electrical conductivity, Figure 9b showed a downward trend in the electrical conductivity of the sample containing slag. The electrical conductivity of the SCC6 design (control design containing Sirjan pozzolan) has decreased by 18% compared to the SCC10 design (containing FSiMn aggregate). According to the obtained results, Sirjan pozzolan shows less electrical conductivity in similar conditions than Khash pozzolan. Since the reduction of electrical conductivity indicates an increase in the durability of concrete, the addition of FSiMn aggregate has reduced the electrical conductivity and so has increased the durability of concrete.

6. Conclusions

In summary, based on the results of this research, the compressive strength of green SCC is, on average, 18% higher than conventional SCC. Moreover, the electrical resistance of green concrete is, on average, 26% higher than SCC without FSiMn aggregate, which indicates an increase in the durability of concrete. The permeability to chloride ions of green SCC is, on average, 20% lower, which indicates an increase in resistance to the penetration of harmful ions into the concrete.

In addition, the electrical conductivity of green SCC is 20% less than ordinary SCC, which indicates an increase in the durability of green concrete compared to ordinary concrete. Sirjan pozzolan in all durability tests has shown better performance than Khash pozzolan, while Khash pozzolan has higher initial compressive strength. Due to the high fracture of FSiMn aggregate compared to natural aggregates, in order to maintain the proper performance and smoothness of green SCC, the use of concrete additives, including superplasticizers, is recommended.

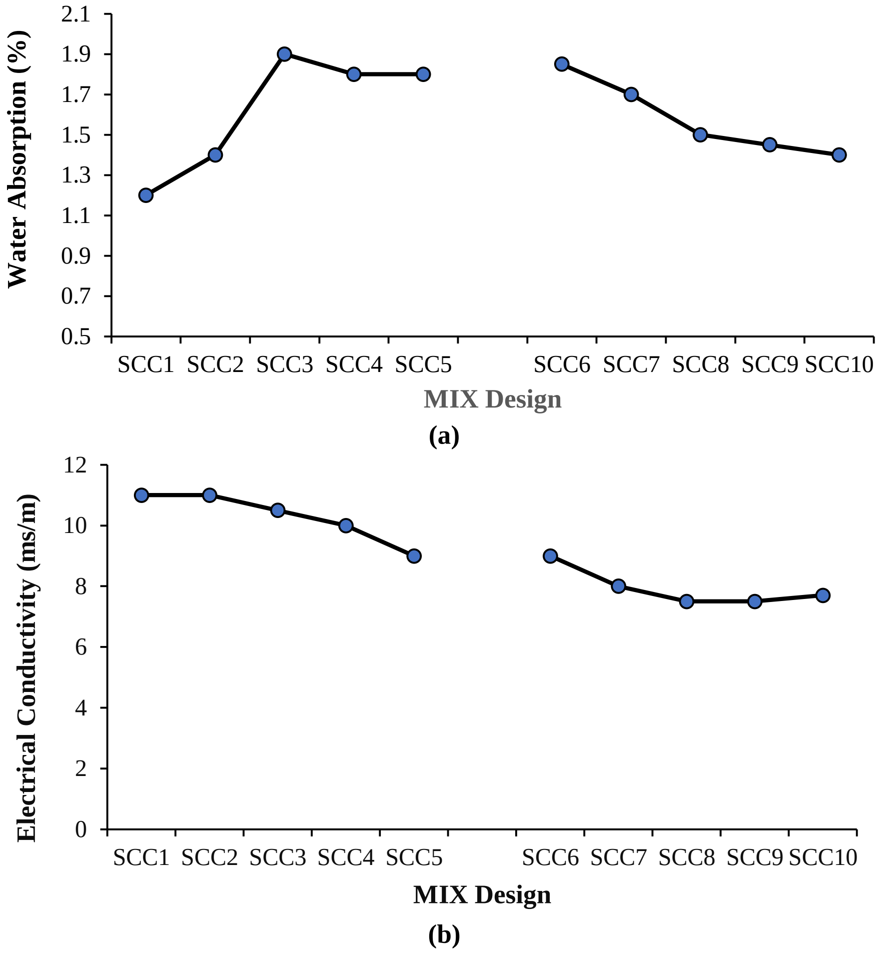

Fig. 9. a) Half-hour water absorption test; and b) Electrical conductivity test

Besides, due to the simultaneous use of both natural pozzolans and artificial pozzolana (FSiMn), the results of this research show that the combination of these two pozzolans at the same time in the concrete mixing design can create a new approach for other researchers to improve both the mechanical properties and the durability of concrete in the future. In this regard, the study of the microstructure of SCC produced from both natural pozzolan and FSiMnS by X-Ray Diffraction (XRD), Scanning Electron Microscope (SEM), and Thermal Gravimetric Analysis (TGA) is recommended for future studies. Moreover, the results of this research reveal the advantages of green concrete, which is related to environmental concerns such as reducing the consumption of natural aggregates, preventing further destruction of natural mine, and reducing environmental pollution caused by slag depots in nature.

7. Declaration

During the preparation of this work, no AI tool was used.

8. References

Afshoon, I. and Sharifi, Y. (2020). “Utilization of micro copper slag in SCC subjected to high temperature”, *Journal of Building Engineering*, 29, 101128, https://doi.org/10.1016/j.jobe.2019.101128.

Amran, M., Murali, G., Khalid, N.H.A., Fediuk, R., Ozbakkaloglu, T., Lee, Y.H., Haruna, S. and Lee, Y.Y. (2021). “Slag uses in making an ecofriendly and sustainable concrete: A review”, *Construction and Building Materials*, 272, 121942, https://doi.org/10.1016/j.conbuildmat.2020.121942.

ASTM International. (2024). *ASTM C150/C150M-Standard specification for Portland cement*, West Conshohocken, PA: ASTM International.

ASTM International. (2025a). ASTM C127-*Standard test method for relative density (specific gravity) and absorption of coarse* *aggregate*, West Conshohocken, PA: ASTM International.

ASTM International. (2025b). *ASTM C192/C192M- Standard practice for making and curing concrete test specimens in the laboratory*, West Conshohocken, PA: ASTM International.

ASTM International. (2025c). *ASTM C1202- Standard test method for electrical indication of concrete's ability to resist chloride ion penetration*, West Conshohocken, PA: ASTM International.

British Standards Institution. (2010). *BS EN 12350-9:2010- Testing fresh concrete: Self-compacting concrete. V-funnel test*, London: BSI.

British Standards Institution (2020). *BS 1881-122:2011 + A1:2020- Testing concrete. Method for determination of water absorption.* London: BSI.

Buruiana, D.L., Ghisman, V., Carp, G.B. and Axente, E.R. (2022). "Valorification of ferroalloy slag waste for environmental protection", *42nd Madrid International Conference on Advances in Science and Technology*, Madrid, Spain, https://doi.org/10.17758/heaig10.dir0622104.

Dey, S., Kumar, V.V.P. and Phani Manoj, A.V. (2022). "An experimental study on strength and durability characteristics of self-curing self-compacting concrete", *Structural Concrete*, 23(5), 3169-3198, https://doi.org/10.1002/suco.202100446.

European Committee for Standardization. (2011). *EN 12350-10:2011- Testing fresh concrete. Self-compacting concrete- L-box test*, Brussels: CEN.

Gencel, O., Karadag, O., Oren, O.H. and Bilir, T. (2021). "Steel slag and its applications in cement and concrete technology: A review", *Construction and Building Materials*, 283, 122783, https://doi.org/10.1016/j.conbuildmat.2021.122783.

Guo, Z., Jiang, T., Zhang, J., Kong, X., Chen, C. and Lehman, D.E. (2020). "Mechanical and durability properties of sustainable self-compacting concrete with recycled concrete aggregate and fly ash, slag and silica fume", *Construction and Building Materials*, 231, 117115, https://doi.org/10.1016/j.conbuildmat.2019.117115.

Gupta, N. and Siddique, R. (2020). "Durability characteristics of self-compacting concrete made with copper slag", *Construction and Building Materials*, 247, 118580, https://doi.org/10.1016/j.conbuildmat.2020.118580.

Institute of Standards and Industrial Research of Iran (ISIRI). (2025). *ISIRI 389- Portland cement-specifications*, Karaj, Iran: ISIRI.

Jindal, A., Rn, G.D., Kumar, P., Kumar, V. and Rana, D. (2023). "Rehabilitation prospects of concrete pavements with self-compacting concrete containing wollastonite micro-fiber", *Civil Engineering Infrastructures Journal*, 56(2), 221-233, https://doi.org/https://doi.org/10.22059/ceij.2023.341456.1828.

Karakurt, C. and Dumangöz, M. (2022). "Rheological and durability properties of self-compacting concrete produced using marble dust and blast furnace slag", *Materials*, 15(5), 1795, https://doi.org/10.3390/ma15051795.

Luo, B., Wang, D. and Mohamed, E. (2022). "Study on mechanical properties and durability of alkali-activated silicomanganese slag concrete (AASSC)", *Buildings*, 12(10), 1621, https://doi.org/10.3390/buildings12101621.

Marinković, S., Radonjanin, V., Malešev, M. and Ignjatović, I. (2010). "Comparative environmental assessment of natural and recycled aggregate concrete", *Waste Management*, 30(11), 2255-2264, https://doi.org/10.1016/j.wasman.2010.04.012.

Mohamed, O.A. and Najm, O.F. (2017). "Compressive strength and stability of sustainable self-consolidating concrete containing fly ash, silica fume, and GGBS", *Frontiers of Structural and Civil Engineering*, 11, 406-411, https://doi.org/10.1007/s11709-016-0350-1.

Mohan, A. and Mini, K.M. (2018). "Strength studies of SCC incorporating silica fume and ultra-fine GGBS", *Materials Today: Proceedings*, 5(11), 23752-23758, https://doi.org/10.1016/j.matpr.2018.10.166.

Nath, S.K., Randhawa, N.S. and Kumar, S. (2022). "A review on characteristics of silico-manganese slag and its utilization into construction materials", *Resources, Conservation and Recycling*, 176, 105946, https://doi.org/10.1016/j.resconrec.2021.105946.

Rahat Dahmardeh, S., Sargazi Moghaddam, M.S. and Mirabi Moghaddam, M.H. (2021). "Effects of waste glass and rubber on the SCC: rheological, mechanical, and durability properties", *European Journal of Environmental and Civil Engineering*, 25(2), 302-321, https://doi.org/10.1080/19648189.2018.1528891.

Santamaría, A., Orbe, A., Losañez, M.M., Skaf, M., Ortega-Lopez, V. and González, J.J. (2017). "Self-compacting concrete incorporating electric arc-furnace steelmaking slag as aggregate", *Materials and Design*, 115, 179-193, https://doi.org/10.1016/j.matdes.2016.11.048.

Sharifi, Y. (2012). "Structural performance of self-consolidating concrete used in reinforced concrete beams", *KSCE Journal of Civil Engineering*, 16(4), 618-626, https://doi.org/10.1007/s12205-012-1517-5.

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

Sharifi, Y., Houshiar, M. and Aghebati, B. (2013). "Recycled glass replacement as fine aggregate in self-compacting concrete", *Frontiers of Structural and Civil Engineering*, 7, 419-428, https://doi.org/10.1007/s11709-013-0224-8.

Siddique, R. (2019). *Self-compacting concrete: materials, properties and applications*, Woodhead Publishing Series in Civil and Structural Engineering, https://doi.org/10.1016/C2018-0-01683-7.

Tamayo, P., García del Angel, G., Setién, J., Soto, A. and Thomas, C. (2023). "Feasibility of silicomanganese slag as cementitious material and as aggregate for concrete", *Construction and Building Materials*, 364, 129938, https://doi.org/10.1016/j.conbuildmat.2022.129938.

Yön, M.Ş., Yön, B., Karataş, M. and Benli, A. (2024). "Sustainable use of boron waste and volcanic scoria in slag-based self-compacting alkali-activated mortars: fresh, mechanical and durability properties", *Sustainable Chemistry and Pharmacy*, 41, 101664, https://doi.org/10.1016/j.scp.2024.101664.