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RESEARCH PAPER

Effect of Concrete Performance on Corrosion Behavior of Pre-Rusted Rebar in Reinforced Concrete

Moein Khoshroo[1] · **Parviz Ghoddousi**[1]

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Abstract
This research focuses on a significant problem: the impact of self-compacting concrete's quality on the decline in corrosion caused by the usage of pre-rusted rebar in reinforced concrete structures within the coastal environment of the Persian Gulf. To investigate this matter, the performance of self-compacting concrete and ordinary concrete was evaluated when utilizing pre-rusted rebar with varying degrees of rust. To enhance the quality of the concrete samples and ensure a more precise evaluation, silica fume, zeolite, and two different water-to-cement ratios were added to the concrete mixes. Several tests were conducted to assess the concrete's quality, including viscosity, yield stress, water volume absorption, total porosity, compressive strength, electrical resistance, electrical conductivity, rapid chloride permeability, rapid chloride migration, and chloride diffusion coefficient. In addition, half-cell potential and intensity corrosion tests were performed to evaluate the steel corrosion in reinforced concrete. The findings indicate that the concrete's quality and the corrosion of the rebar surface significantly influence the corrosion of pre-rusted steel in reinforced concrete. When rebars with different surface conditions, self-compacting concrete reduced corrosion intensity by 17% to 55% compared to ordinary concrete. Furthermore, adding supplementary cement materials and reducing the ratio of the water to cementitious material in self-compacting concrete resulted in a 13% to 48% greater reduction in the risk of corrosion compared to similar samples in ordinary concrete.

Keywords Self-compacting concrete · Pre-rusted rebar · Steel corrosion · Surface conditions

1 Introduction

The most significant factor that affects the longevity and failure of concrete structures in the Persian Gulf is steel corrosion in reinforced concrete buildings [1]. A substantial amount of money is spent each year on repairing and rebuilding buildings damaged by this issue [2]. One contributing factor to the creation and acceleration of the corrosion process is the usage of rebars with varying degrees of rust due to improper storage. While research has been conducted on the corrosion process caused by such rebars, specific issues still require further investigation. One crucial aspect that needs to be studied is the role of concrete type and quality in preventing corrosion of reinforced concrete when pre-rusted rebars are used.

Chloride emissions and carbonation are the two primary causes of steel corrosion in reinforced concrete structures [3]. Due to the high levels of airborne chlorine in the Persian Gulf, along with the high temperatures and humidity, corrosion of steel in reinforced concrete is predominantly of the chloride type [4]. The required chloride ions to initiate the corrosion process can be obtained from internal sources, such as chloride ion-contaminated materials, and external sources, such as air and water [5]. The risk of using contaminated materials can be reduced by implementing proper storage procedures and conducting relevant testing before applying the concrete. However, mitigating the risk of chloride penetration into the concrete from external sources can be achieved by improving the quality of the concrete.

✉ Parviz Ghoddousi
Ghoddousi@iust.ac.ir

Moein Khoshroo
khoshroo_moein@civileng.iust.ac.ir

[1] School of Civil Engineering, Iran University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran

Modifications in the design of concrete mixes can significantly impact chloride entry [6]. The resistance to chloride penetration in concrete is primarily determined by its transfer properties, which include permeability, diffusion, and adsorption. In the early stage, the pore structure of the cement paste in concrete hardens when exposed to external chlorides. Furthermore, the chemistry of hydrated cement paste affects the concrete's ability to chemically bind chlorides, preventing them from bonding with the steel in reinforced concrete.

Numerous studies have examined self-compacting and ordinary concrete's mechanical properties and durability. The research conducted by [7] investigated the impact of various environmental conditions from the Oman Sea on the mechanical characteristics of self-compacting concrete (SCC) and regular concrete. The results indicated that the diffusion coefficient of SCC was 10% and 15% lower than regular concrete at 28 and 150 days, respectively. Moreover, the surface chloride concentration of self-compacting concrete was 18% and 52% lower than that of regular concrete. Another study [8] compared self-compacting concrete's and conventional concrete's durability with varying water-to-cement ratios in a coastal environment. The findings revealed that SCC exhibited 11.4% higher electrical resistance than ordinary concrete. Several researchers [9, 10] concluded that SCCs demonstrated lower porosity, chloride absorption, and release than conventional concrete. However, it is essential to note that contrary findings were also reported in several studies [11, 12].

The effect of using self-compacting concrete exposed to external sources of chloride ions on steel corrosion in reinforced concrete has received limited attention. However, a few research studies have addressed this subject. Studies [13, 14] noted that the likelihood of corrosion in self-compacting concrete mixtures is low until the age of 360 days. Another study [15] found that the corrosion rate for self-compacting concrete was approximately 2–12 times lower than ordinary concrete. Furthermore, research [16] evaluated the performance of four self-compacting concrete mixtures with different combinations of additives, such as silica fume, metakaolin, and limestone powder, against corrosion. Electrochemical tests in [17] compared the onset of steel corrosion in self-compacting concrete and conventional concrete, revealing that self-compacting concrete samples demonstrated superior corrosion control. Additionally, paper [18] investigated the long-term corrosion of rebars in various types of concrete commonly used in construction, demonstrating that rebars in self-compacting concrete exhibited higher resistance than those in ordinary concrete. In a study on reinforced concrete beams [19], corrosion in self-compacting concrete samples outperformed normal concrete samples in terms of intensity and corrosion potential.

In addition to the type of concrete (ordinary or SCC), the use of Supplementary Cementitious Materials (SCMs) can influence the performance of concrete. Studies [20–22] have shown that the use of cementitious additives affects the chloride permeability performance of high-strength concrete and significantly reduces the rate of chloride penetration and migration. Furthermore, in the research [23], it was observed that using natural pozzolans reduces water absorption, increases porosity, and generally improves the transport properties of concrete. Based on the findings of the study [24], the use of cementitious materials in self-compacting concrete also improves the properties of both fresh and hardened concrete. Moreover, in research [25], it was reported that using cementitious additives in high-strength self-compacting concrete improves transport properties and reduces chloride permeability.

Therefore, based on the instances above, it can be concluded that improving the functionality and quality of concrete is crucial in reducing steel corrosion in reinforced concrete in chloride-contaminated areas. This can be achieved mainly by utilizing self-compacting concrete incorporating supplementary cementitious materials (SCMs) and a lower water-to-cement ratio. However, it is essential to note that most studies focused on the impact of concrete type and quality when used with rebar that had suitable surface conditions and no rust. In reality, in many construction projects in the Persian Gulf, steel rebars often have a rusty surface and are contaminated with chloride due to inadequate attention to proper storage. Although a few studies [26–31] have examined the effect of rusted rebar on reinforced concrete corrosion, most researchers [26–28, 30] reported increased corrosion intensity and potential when such rebar was used. Therefore, there is a significant need to investigate the effect of enhancing concrete quality on corrosion when utilizing such rebars.

Hence, the primary objective of this study is to determine the influence of self-compacting concrete quality on steel corrosion in reinforced concrete when pre-rusted rebar is employed. Two types of concrete were used to assess the impact of quality: ordinary concrete and self-compacting concrete with SCMs, using water-to-cementitious materials ratios of 0.4 and 0.5. Additionally, pre-rusted rebar samples with varying degrees of corrosion, subjected to real-world conditions of the project, were used for reinforcing the concrete.

2 Laboratory Program

2.1 Materials

Table 1 presents the chemical properties of the powder materials used in this research. The type II cement, zeolite,

Table 1 Chemical properties of powder materials

Constituents/ property	Cement type II (%)	Limestone powder (%)	Silica fume (%)	Zeolite (%)
SiO_2	20.74	2.80	94.00	67.20
Al_2O_3	4.90	0.35	1.10	10.00
Fe_2O_3	3.50	0.50	1.27	1.20
CaO	62.95	51.22	0.11	1.40
MgO	1.20	1.80	0.14	0.73
SO_3	3.00	1.24	0.28	0.08
Na_2O	0.3	–	0.29	1.22
K_2O	0.51	–	0.25	1.33
L.O.I	1.56	42.06	2.5	12.05

and silica fume utilized in this investigation have densities of 3150, 2140, and 2200 kg/m^3, respectively, and conform to ASTM C150 and ASTM C1240 standards. Stone powder, sand, and gravel used in concrete mix ratios have a maximum size of 0.175, 4.75, and 19 mm, and a density of 2610, 2580, and 2500 kg/m^3, respectively. The ASTM C33 standard was used to granulate stone materials. The workability and performance of concrete mixes are enhanced by using a polycarboxylate-based lubricant with a density of 1100 kg/m^3 according to with ASTM C494 standard. Rebars with a diameter of φ 12 mm were used to reinforce concrete.

2.2 Preparation and Storage of Rebar

To simulate the rusted rebar condition, 1-m samples were placed in two different locations and at two distances within the project environment in the Persian Gulf. The first approach involved placing the samples directly on a wooden spacer without any protection, while in the second approach, the samples were thoroughly enclosed with a plastic cover. Additionally, the samples were positioned at two distances from the sea: 70 m (close) and 300 m (far). These specific distances were chosen to reflect the actual conditions of the project closely. The decision to use these distinctions was based on the findings of a study conducted by [32], which demonstrated that the corrosion of chloride-type steel decreases with increasing distance from the sea across various beaches, accompanied by a decrease in the amount of suspended chlorine in the air. Furthermore, for comparative purposes, a reference sample of rebar in its normal condition (as received from the factory) and rebar exposed to accelerated corrosion through the constant current method were also included in the study.

For a detailed explanation of this method, please refer to the research conducted by [33]. The weight loss resulting from corrosion (measured through gravimetry) was utilized to assess the rust condition of the rebar surface. The weight loss caused by corrosion was determined using brushing following the standard ASTM G1 method. The weight reduction and rebar ranking results are presented in Table 2.

By implementing these specific methodologies, we can effectively replicate and evaluate the effects of environmental factors and corrosion methods on the condition of the rebars. This comprehensive analysis provides valuable insights into the behavior and performance of the materials, thereby contributing to the development of effective corrosion prevention strategies for reinforced concrete structures in chloride-contaminated areas.

2.3 Mixture Proportions

Six different mixing ratios were utilized to examine the impact of the self-compacting concrete's performance on the corrosion of pre-rusted steel in concrete. Based on the findings of earlier studies [34, 35], the optimum ratio of SCMs for silica fume 8% and zeolite 15% of cement weight has been chosen. Additionally, six proportions of ordinary concrete mix with the same composition as the self-compacting concrete samples have been employed for more precise comparison. The quantities of the concrete mix used in this study are shown in Table 3.

Viscosity, yield stress, water volume absorption, total porosity, compressive strength, electrical resistance, electrical conductivity, rapid chloride permeability, rapid chloride migration, chloride diffusion coefficient, half-cell corrosion potential, and corrosion current intensity are among the tests that were performed. The samples were cured till the test age in accordance with ASTM C156 standard procedure, in a saturated lime water solution. Additionally, after being cured for 7 days in saturated lime water until the test age, the samples related to determining the potential and intensity of the corrosion current were put in a 5% NaCl solution. This was done to speed up the corrosion process in accordance with the technique described in the study by [36].

2.4 Experiments

2.4.1 Fresh and Hardened Concrete Tests

A coaxial rheometer with controllable speed was used to measure the yield stress of plastic viscosity as the rheological properties of self-compacting concrete. According

Table 2 The condition of the surface of the rebars

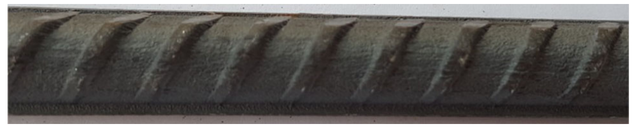
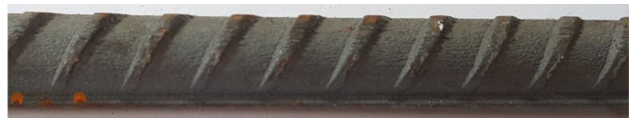
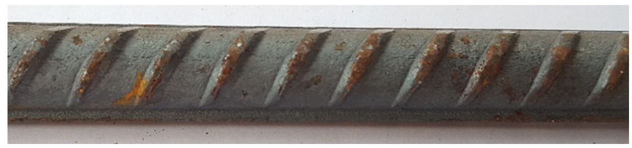
Sample	Weight loss (%)	Description	Surface conditions
S1	1.38	Ordinary rebar is received from the factory	
S2	4.71	Rebar stored away from the sea with protection	
S3	5.38	Rebar stored near the sea with protection	
S4	16.74	Rebar stored away from the sea	
S5	19.41	Rebar stored near the sea	
S6	22.98	Laboratory rusted rebar	

Table 3 Mixture proportions of concrete

Concrete	Code	*W/B*	Cement (Kg/m^3)	Water (Kg/m^3)	SF (Kg/m^3)	Z (Kg/m^3)	LP (Kg/m^3)	Aggregate (Kg/m^3)	SP
Ordinary	C0.4	0.4	400	160	–	–	–	1780	0.5
	C0.5	0.5	400	200	–	–	–	1678	0.2
	CSF0.4	0.4	368	160	32	–	–	1769	0.7
	CSF0.5	0.5	368	200	32	–	–	1666	0.25
	CSZ0.4	0.4	308	160	32	60	–	1746	1.25
	CSZ0.5	0.5	308	200	32	60	–	1643	0.35
SCC	S0.4	0.4	400	160	–	–	150	1619	1.2
	S0.5	0.5	400	200	–	–	150	1528	0.8
	SSF0.4	0.4	368	160	32	–	150	1630	1.6
	SSF0.5	0.5	368	200	32	–	150	1516	1
	SSZ0.4	0.4	308	160	32	60	150	1516	1.9
	SSZ0.5	0.5	308	200	32	60	150	1596	1.3

SF silica fume, *Z* zeolite, *LP* limestone powder, *SP* superplasticizer (% by weight of cementitious material)

Table 4 Fresh and hardened concrete tests

Code	Slump (flow) (mm)	Standard deviation (mm)	T50 (S)	Standard deviation (S)	Fresh density (Kg/m^3)	Standard deviation (Kg/m^3)	Hardened density (Kg/m^3)	Standard deviation (Kg/m^3)
C0.4	120	12	–	–	2371	27	2292	17
C0.5	130	10	–	–	2320	24	2263	28
CSF0.4	110	13	–	–	2365	32	2276	38
CSF0.5	120	15	–	–	2293	22	2247	26
CSZ0.4	95	12	–	–	2295	37	2236	29
CSZ0.5	100	11	–	–	2267	25	2210	43
S0.4	720	26	2.8	0.25	2384	36	2315	29
S0.5	750	35	2.1	0.34	2344	33	2284	31
SSF0.4	685	21	3.15	0.39	2374	28	2294	25
SSF0.5	712	29	2.6	0.28	2305	19	2268	40
SSZ0.4	663	25	3.35	0.31	2302	36	2249	22
SSZ0.5	679	28	3.15	0.39	2279	27	2223	24

to study [37], this device measures the torque applied to the blades when immersed in concrete. Also, to determine the volumetric absorption of water and the volume of permeable pores of concrete samples, the instructions expressed in ASTM C642 standard were used. A compressive strength test evaluated the mechanical properties of concrete. Cubic specimens (100 × 100 × 100 mm) were loaded at 28 days of age according to BS1881-PART116 to perform the compressive strength test.

Electrical resistivity test is applied to evaluate the electrochemical properties of concrete at 28 days of age according to the presented method by [38]. In addition, according to ASTM C1202, concrete samples' rapid chloride permeability test (RCPT) was measured at 28 days of age. Also, an electrical conductivity test according to ASTM C1760 standard and a chloride ion migration test (RCMT) according to NT BUILD 492 standard were performed to determine the resistance of concrete against chloride ion penetration at the age of 28 days on concrete samples.

The standard method of ASTM C1556 was used to determine the apparent diffusion coefficient of chloride ions in concrete. Fick's second law [39] was used to obtain the chloride ion diffusion coefficient from Eq. 1:

$$\frac{C(x,t)}{C_0} = 1 - \mathrm{erf}\left(\frac{x}{\sqrt{4D_c t}}\right), \quad (1)$$

$$\mathrm{erf}_{(x)} = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\mathrm{dt}. \quad (2)$$

In this equation, x is the distance from the surface (mm), t the duration of chloride exposure (days), D_c the effective chloride diffusion coefficient (m^2/s), C_0 the weight percentage of chloride ions on the concrete surface, and $C(x, t)$ the weight percentage of chloride ion at depth x relative to the surface at time t. erf is also an error function expressed according to Eq. 2 [40].

2.4.2 Corrosion Tests of Steel in Reinforced Concrete

Half-cell potential corrosion test was performed according to the ASTM C876 standard guidelines using a voltmeter and a reference electrode at different ages on the samples. The cylindrical specimens used to test half-cell potential and corrosion intensity in this study had a height of 200 mm and a diameter of 60 mm.

In this research, the corrosion intensity test was performed on the samples made for the half-cell test (cylindrical samples 200 × 60 mm) using a potentiostat device according to the ASTM G102 standard.

To increase the accuracy and reduce inadvertent laboratory error, the average results of three tests in each experiment were recorded as the final result.

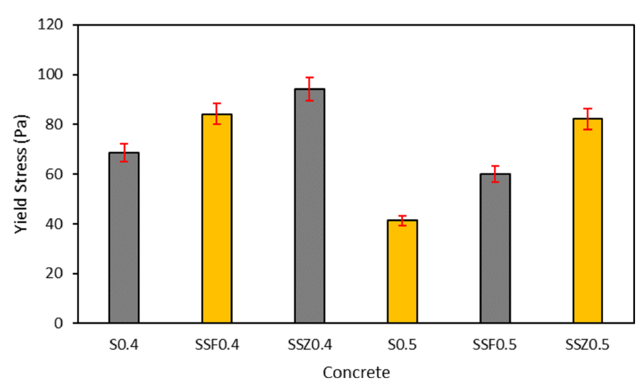


Fig. 1 Yield stress

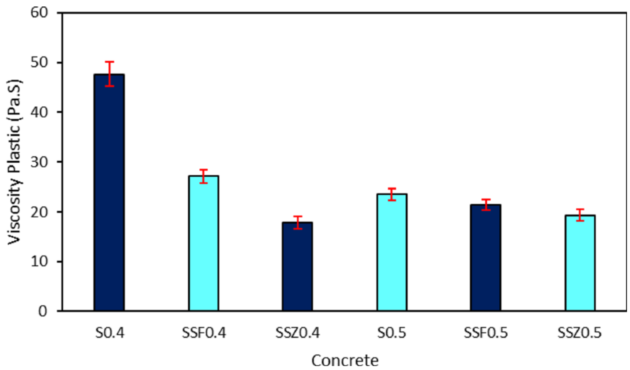


Fig. 2 Viscosity plastic

3 Results and Discussion

3.1 Fresh Concrete Tests and Special Weight

According to the slump test results presented in Table 4, the inclusion of silica fume in fresh concrete leads to a reduction in flow and workability, and this influence is further amplified by the addition of zeolite alongside silica fume. The diminished workability observed in concrete with supplementary cementitious materials (SCMs) can be attributed to their high specific surface area within the internal structure. Additionally, a decrease in a slump was observed as the ratio of water to cementitious material decreased. To compensate for the decrease in workability and achieve the desired slump, an additional superplasticizer was added. In the case of self-compacting concrete, the workability is typically lower compared to ordinary concrete, especially when SCMs are employed and the ratio of water to cementitious material is reduced. Consequently, higher consumption of superplasticizers is necessary. It was found that the maximum slump values for both regular and self-compacting concrete were obtained when the water-to-cement ratio was set at 0.5.

Also, samples with a ratio of 0.4 water to cementitious materials used the most superplasticizer. These samples contained silica fume and zeolite. In comparison to the lowest superplasticizer usage, which corresponds to sample C0.5 with 0.2% cementitious materials by weight, the SSZ0.4 and CSZ0.4 samples required 89% and 84% more superplasticizer, respectively. Studies [41, 42] have also reported a reduction in slump and workability when zeolite is utilized in fresh concrete.

The T_{50} test measures concrete viscosity. The results of the slump flow tests on self-compacting concrete indicate that the samples containing silica fume and zeolite with water-to-cementitious material ratios of 0.4 and 0.5 exhibit the highest values. As shown in Table 4, achieving the target slump in samples containing both zeolite and silica fume requires a higher amount of superplasticizer compared to other mixtures. Consequently, the viscosity of these samples is higher, resulting in a more significant T50 value and a smaller slump flow diameter. These findings hold for both regular and self-compacting concrete and align with the results of previous research [43, 44].

In terms of density, an increase in the ratio of water to cementitious material leads to a decrease in density. This trend is also observed in concrete containing silica fume and zeolite SCMs due to their lower specific gravity compared to cement. On the other hand, self-compacting concrete, which incorporates limestone powder with a higher specific gravity than aggregates, exhibits a higher density compared to ordinary concrete due to its greater compressibility. Similar findings have been reported in other studies [35].

Yield stress and plastic viscosity are crucial indicators of the rheological properties of self-compacting concrete, which affect its mechanical properties and durability. The experimental results in Fig. 1 indicate that increasing the water-to-cementitious materials ratio from 0.4 to 0.5 reduces the yield stress. The addition of silica fume and zeolite to the concrete mix also increases the yield stress, which is attributed to the finer particle size of SCMs compared to cement. The percentage of superplasticizers used effectively determines the yield stress. Our work

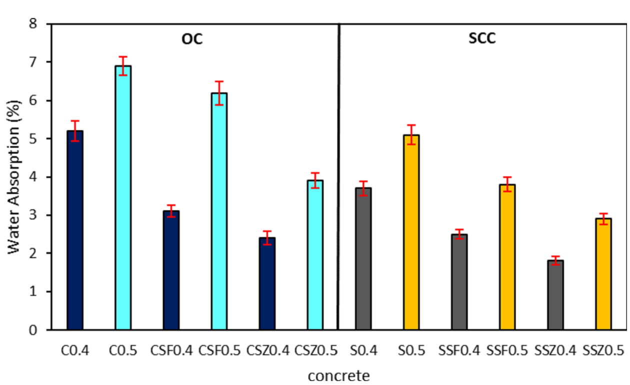


Fig. 3 Water absorption

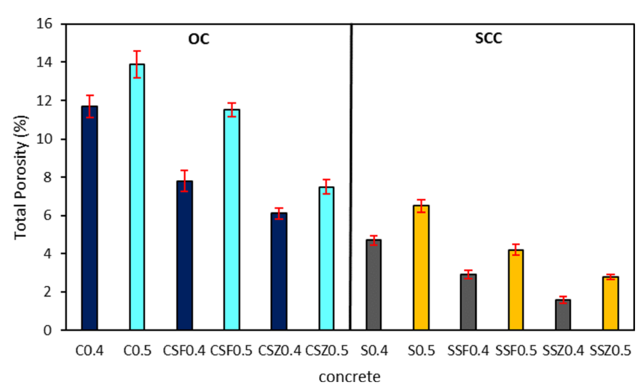


Fig. 4 Total porosity

aimed to minimize the use of superplasticizers while achieving the desired slump and mitigating the negative effects of excessive usage.

In addition, plastic viscosity tests (Fig. 2) showed a decrease in the amount of SCMs in the mixture with their addition, especially when silica fume and zeolite were combined. Increasing the ratio of the water to cementitious material leads to a decrease in plastic viscosity. These findings align with the report [40].

3.2 Volumetric Absorption of Water

Water absorption is a test used to assess the permeability of concrete, and the corresponding results are presented in Fig. 3. Generally, self-compacting concrete exhibits lower water absorption compared to ordinary concrete samples due to its dense microstructure. This indicates that self-compacting concrete possesses a lower density and fewer large cavities than ordinary concrete. Among the samples, the lowest water absorption is observed in the SSZ0.4 sample, while the highest is recorded in the C0.5 sample. The results demonstrate that reducing the water-to-cement ratio leads to a decrease in water absorption, particularly evident in self-compacting concrete.

The inclusion of silica fume as a supplementary cementitious material (SCM) in the SSF0.4 sample results in a 20% reduction in water absorption compared to the CSF0.4 sample of ordinary concrete. Similarly, in the SSF0.5 sample compared to the CSF0.5 sample, a significant decrease of 38% in water absorption is observed. The combined use of two SCMs, zeolite and silica fume, further improves the reduction in water absorption. The SSZ0.4 and SSZ0.5 samples exhibit a decrease in water absorption of 25% and 27%, respectively, compared to the corresponding samples of CSZ0.4 and CSZ0.5 ordinary concrete. This improvement can be attributed to the fine structure of SCMs, which act as fillers for voids between cement and aggregates, resulting in a larger volume of C–S–H gel through interaction with calcium hydroxide (CH). Consequently, water absorption and porosity are reduced [45]. The volumetric water absorption test confirms the superior quality of the self-compacting concrete samples. Similar findings have been reported in previous research [9].

3.3 Total Porosity

The results of the total porosity test are shown in Fig. 4. The primary reason for using supplementary cementitious materials (SCMs) is to create a mixture with a homogeneous microstructure. Furthermore, reducing the ratio of water to cementitious materials effectively decreases the total porosity. In the case of self-compacting concrete (SCC) samples, the total porosity is consistently lower than that of the corresponding ordinary concrete samples across all mixture ratios. This improvement can be attributed to the incorporation of stone powder and finer aggregate in this particular type of concrete. The obtained results indicate that, at a water-to-cementitious materials ratio of 0.4, the total porosity of S, SSF, and SSZ samples is, respectively, 60%, 63%, and 73% lower than that of C, CSF, and CSZ samples. When the water-to-cementitious materials ratio is 0.5, the improvement values for self-compacting concrete compared to ordinary concrete range between 56 and 64%. These findings align with the results of the aforementioned research [45].

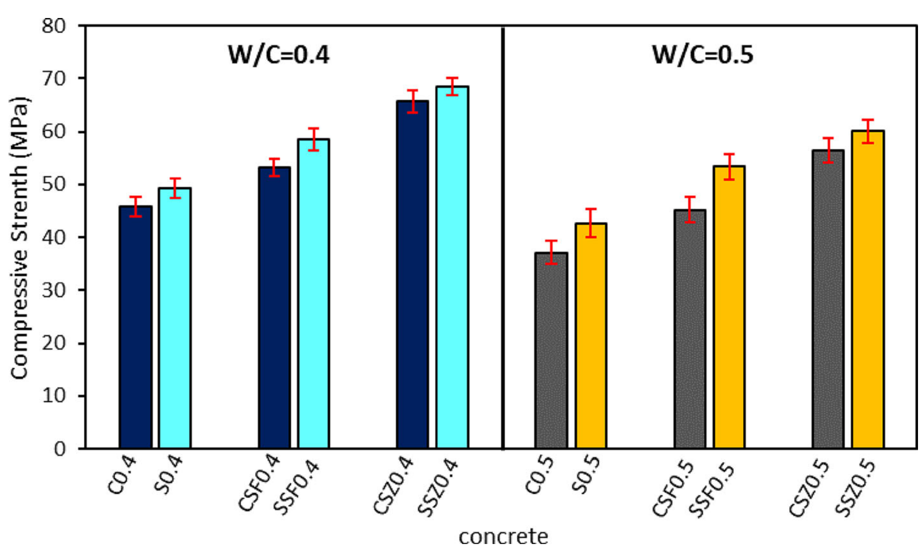


Fig. 5 Compressive strength

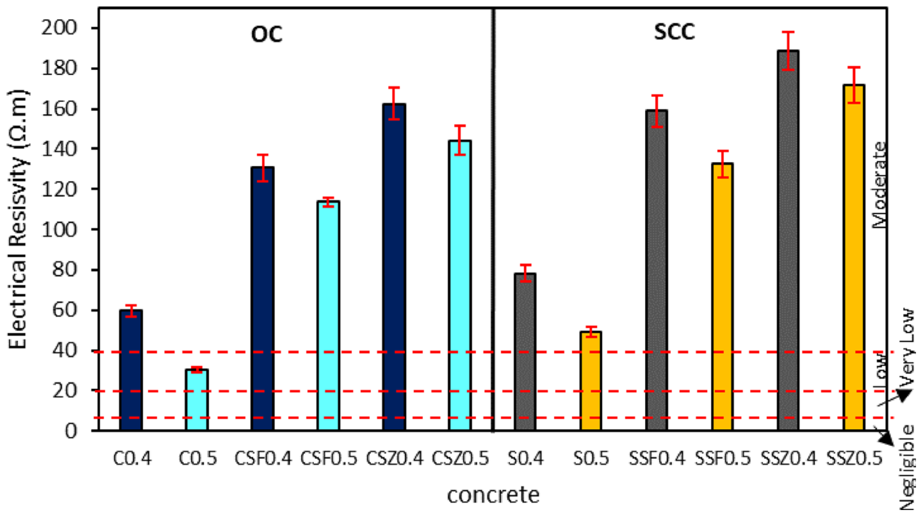


Fig. 6 Electrical resistivity

3.4 Compressive Strength

The compressive strength test results for both self-compacting concrete and ordinary concrete samples are illustrated in Fig. 5. Previous research [46] has demonstrated that reducing the water-to-cement ratio and incorporating supplementary cementitious materials (SCMs) enhances the quality of concrete and increases its compressive strength. Silica fume, for instance, reacts with hydrated calcium hydroxide, limiting the pore size of cement particles and reducing cracking. By utilizing SCMs and their filler effect, the strength of the boundary layer is augmented while significantly reducing porosity. Notably, the SSZ0.4 sample exhibited the highest resistance with a strength of 68 MPa, whereas the lowest resistance was observed in the C0.5 sample, reaching only 37 MPa. A clear comparison between ordinary and self-compacting concrete samples reveals that self-compacting concrete exhibits superior strength compared to similar ordinary concrete samples. The ability of SCC concrete to flow effortlessly and resist segregation fills the entire concrete formwork without requiring vibration. This characteristic, combined with the compactness and uniformity of self-compacting concrete, significantly contributes to its enhanced compressive strength. In line with research findings [18], self-compacting concrete consistently exhibits higher compressive strength compared to ordinary concrete. The improvement in compressive strength for S, SSF, and SSZ samples, compared to C, CSF, and CSZ samples, at a water-to-cement ratio of 0.4, is 8%, 10%, and 7%, respectively. Similarly, at a water-to-cement ratio of 0.5, the improvement percentages are 15%, 18%, and 8%,

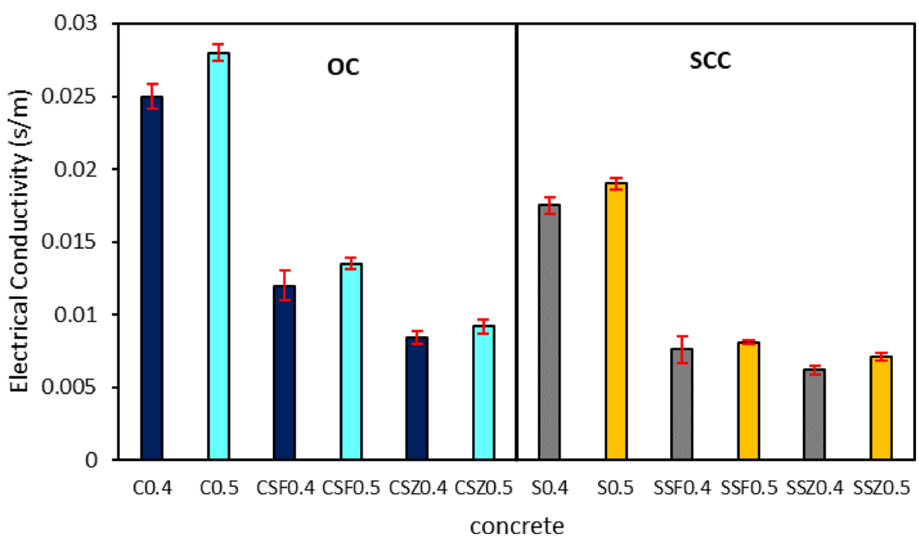


Fig. 7 Electrical conductivity

respectively. Thus, based on the results of this test, it can be concluded that self-compacting samples outperform ordinary concrete samples.

3.5 Electrical Resistivity

The electrical resistivity of concrete serves as a valuable parameter for assessing its resistance to ions that affect its microstructure. A comparison between the S0.4 and C0.4 samples revealed a 10% improvement in electrical resistance for the former, while the S0.5 sample exhibited a 15% improvement compared to the C0.5 sample. Research [14] supports the notion that self-compacting concrete outperforms ordinary concrete with its dense and homogeneous microstructure. Incorporating silica fume further enhances the electrical resistance of self-compacting concrete samples in the water-to-cementitious materials ratios of 0.4 and 0.5, resulting in improvements of 11% and 18%, respectively. Including supplementary cementitious materials (SCMs) amplifies the degree of enhancement in electrical resistance. Alkaline ion concentrations in concrete represent the primary source of ion transfer. By incorporating SCMs, the content of sodium and potassium, which contribute to high conductivity, is reduced in the pore solution, thereby lowering electrical resistance [47, 48]. SSZ0.4 demonstrated the highest electrical resistance among the samples at 189 Ω.m [43]. Additionally, the study indicates that reducing the water-to-cementitious materials ratio increases electrical resistance. Electrical resistance levels are categorized into five ranges, as suggested by [49], ranging from negligible to high. Except for the C0.5 sample, most of the samples in this research exhibited moderate levels of electrical resistance, as depicted in Fig. 6. Overall, self-compacting concrete exhibits superior electrical resistance compared to regular concrete. Please refer to Fig. 6 for the results of the electrical resistance test.

3.6 Electrical Conductivity

The electrical conductivity test of concrete is a crucial assessment that measures the volumetric electrical conductivity of a saturated concrete sample, providing insights into its resistance to chloride ion penetration. Figure 7 illustrates the electrical conductivity values of ordinary and self-compacting concrete samples. The results demonstrate that an increase in the ratio of the water to cementitious material leads to higher electrical conductivity, while the use of supplementary cementitious materials (SCMs) reduces it. Notably, the self-compacting concrete samples exhibit lower electrical conductivity than ordinary concrete. In the case of self-compacting concrete, the S0.4, SSF0.4, and SSZ0.4 samples exhibit reduced electrical conductivity by 30%, 58%, and 35%, respectively, compared to their corresponding ordinary concrete samples.

Similarly, the improvement values for the S0.5, SSF0.5, and SSZ0.5 samples amount to 48%, 43%, and 39%, respectively. Incorporating SCMs in ordinary and self-compacting concrete samples effectively reduces conductivity, a finding also supported by Research [50]. For instance, the decrease in electrical conductivity observed in the SSF0.4 sample is one-third compared to the S0.4 sample and 1.1 times in the CSF0.4 sample compared to the C0.4 sample. In the water-to-cementitious materials ratio of 0.5, these values amount to 1.5 and 1.4 times, respectively. Moreover, when combining SCMs such as silica fume and zeolite with self-compacting and ordinary concrete, a significant improvement of approximately two

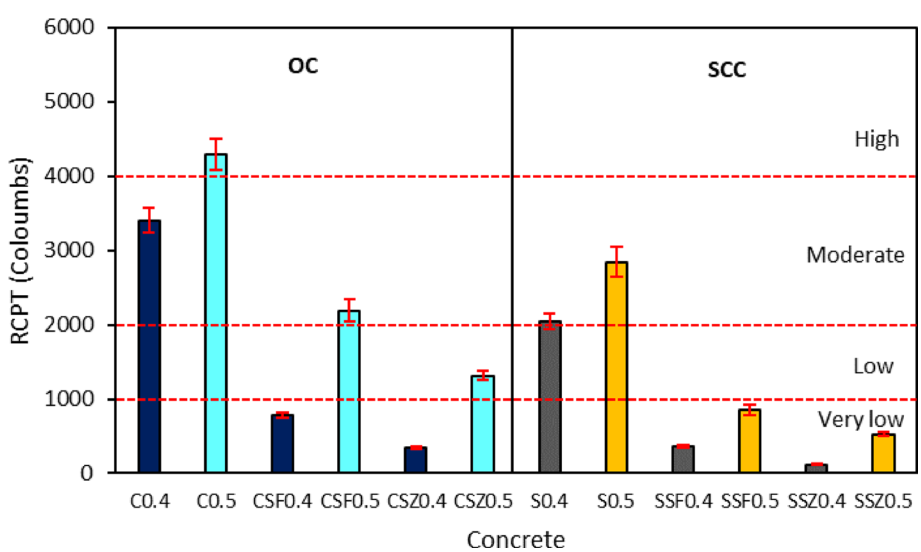


Fig. 8 RCPT

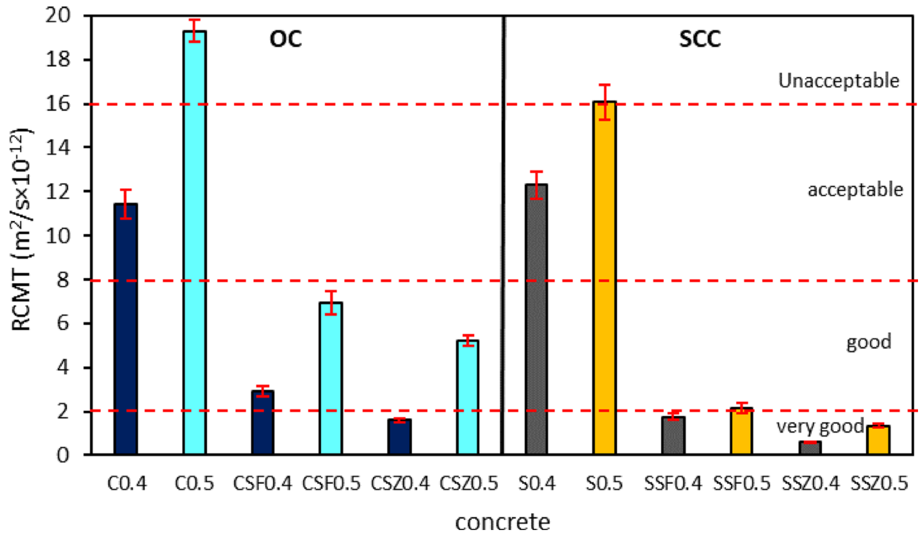


Fig. 9 RCMT

times is achieved compared to the reference sample for each ratio. The assessment of water content has been performed for cementitious materials as well.

3.7 Rapid Chloride Permeability Test (RCPT)

The RCPT test is widely utilized for assessing the permeability of concrete. By reducing the ratio of the water–cementitious material and incorporating supplementary cementitious materials (SCMs), notably when zeolite and silica fume are combined, the RCPT value of concrete is effectively reduced. Using SCMs in concrete serves two purposes: filling the empty spaces between cement paste particles and facilitating the pozzolanic reaction, forming C–S–H. These physical and chemical functions contribute to a reduction in permeability and chloride release [51]. A comparison between ordinary concrete and self-compacting concrete samples reveals that the latter demonstrates lower RCPT values. This can be attributed to self-compacting concrete's homogeneous mixing and cohesion properties [52]. Specifically, the reduction in RCPT values for the S0.4 and S0.5 samples amounts to 39% and 34%, respectively, compared to the C0.4 and C0.5 samples. The addition of silica fume results in a significant improvement of 54% and 60% in the SSF0.4 and SSF0.5 samples, respectively, compared to the corresponding control samples of ordinary concrete. Notably, the combination of silica fume and zeolite samples, leveraging the synergistic effect of SCMs, yields remarkable RCPT reductions of 65% and 60% in the SSZ0.4 and SSZ0.5 samples, respectively, compared to their ordinary concrete counterparts. The results of the RCPT test are illustrated in Fig. 8. According to the ASTM C1202 standard, only the C0.5 sample falls within the high range of the chart. Most self-compacting concrete specimens exhibit very low RCPT values, indicating their excellent resistance to chloride penetration. This classification further confirms the superior performance of self-compacting samples compared to ordinary concrete, which aligns with the findings of a previous report [53].

3.8 Rapid Chloride Migration Test (RCMT)

Figure 9 displays the findings of the chloride ion migration coefficient for the concrete samples. The results indicate that increasing the water-to-cementitious materials ratio enhances the samples' RCMT (Resistance to Chloride Ion Migration), while substituting cement with SCMs increases the resistance of concrete to chloride ion transit. A similar trend is observed in self-compacting concrete, albeit with lower RCMT than ordinary concrete. The sample from SSZ0.4 exhibits the lowest chloride migration coefficient, while sample C0.5 shows the highest.

By reducing the water-to-cementitious materials ratio from 0.5 to 0.4 in samples without SCMs, the chloride migration coefficient decreases by approximately 65%. In samples containing silica fume, this reduction is 1.4 times, and in samples containing a combination of silica fume and zeolite, it reaches 2.3 times. In self-compacting concrete, these reductions amount to 90%, 22%, and 1.25 for S0.4, SSF0.4, and SSZ0.4, respectively. Compared to ordinary concrete, a 49% reduction in chloride migration coefficient is observed in self-compacting concrete at a water-to-cementitious materials ratio of 0.4. This reduction increases to 64% in samples containing silica fume, and in samples with a combination of silica fume and zeolite, it reaches 1.65 times compared to ordinary concrete samples. At a water-to-cementitious materials ratio 0.5, these reductions

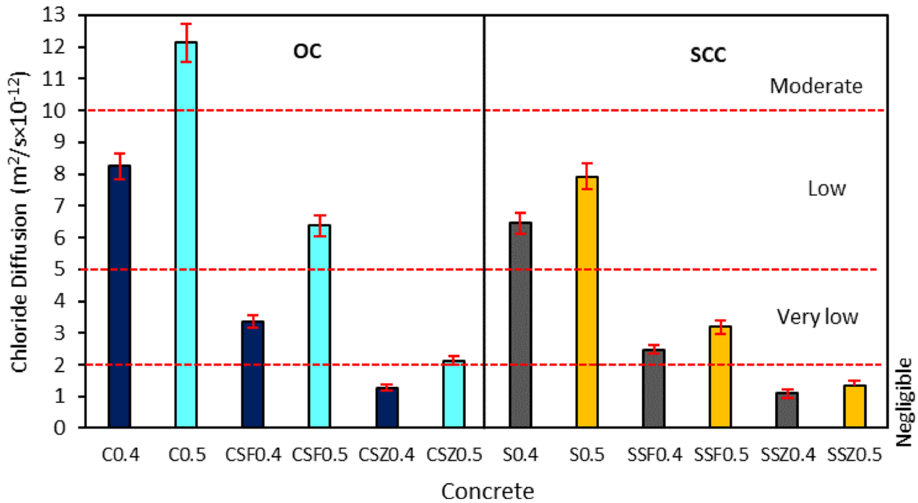


Fig. 10 Chloride ion diffusion

are calculated as 71%, 2.2 times, and 2.86 times, respectively.

What draws more attention to these results is the significant effect of using SCMs in reducing the chloride ion migration coefficient in different types of concrete. Specifically, in ordinary concrete, the migration coefficient is reduced by 2 times at a water-to-cementitious materials ratio of 0.4, and in self-compacting concrete, this reduction reaches 2.6 times. At a water-to-cementitious materials ratio of 0.5, these values increase to 1.5 and 3.6 times, respectively. The reduction is even more substantial when employing a combination of silica fume and zeolite. In ordinary concrete, it measures 5.5 times at a water-to-cementitious materials ratio of 0.4; in self-compacting concrete, it reaches 7.83 times lower. The reduction of the chloride migration coefficient at a water-to-cementitious materials ratio of 0.5 is 2.3 times for ordinary concrete and 6.5 times for self-compacting concrete.

According to the classification provided in [54], the resistance of concrete to chloride penetration is divided into four categories based on the chloride ion migration test conducted at 28 days of age. In this classification, an RCMT value [in terms of ($m^2/s \times 10^{-12}$)] below 2 falls into the very good range, between 2 and 8 is categorized as good, between 8 and 16 is considered acceptable, and above 16 is classified as unacceptable in terms of resistance to chloride penetration. Applying this classification, sample C0.5 is the only one in the unacceptable range, while samples CSZ0.4, SSF0.4, SSZ0.4, and SSF0.5 fall within the very good range. Samples CSF0.4, CSF0.5, CSZ0.5, S0.4, and SSF0.5 are in the good range, and samples C0.4 and S0.5 are categorized as acceptable.

3.9 Apparent Chloride Diffusion Coefficient

Chloride diffusion in concrete is controlled through diffusion tests. Consistent with the excellent performance observed in other tests conducted in this study, self-compacting samples also exhibited better conditions in this test. The results of this experiment are depicted in Fig. 10. Including SCMs reduced the diffusion coefficient in all samples due to their filling properties, pore reduction, and ion transfer capabilities. Decreasing the ratio of the water to cementitious material reduced the diffusion coefficient through a denser microstructure and relative porosity reduction. However, the improvements from decreasing the ratio of the water to cementitious material were less significant than the changes induced by adding SCMs. The sample with the lowest diffusion coefficient was SSZ0.4, with a value of 1.1 ($m^2/s \times 10^{-12}$), while the highest emission coefficient was observed in sample C0.5, with a value of 12.1 ($m^2/s \times 10^{-12}$). Similar findings were reported in the study [55]. The reduction coefficient of the S0.4 sample compared to the C0.4 sample was 14%, and for the S0.5 sample compared to the C0.5 sample, it was 22%. Moreover, samples incorporating silica fume in self-compacting concrete exhibited diffusion coefficients of 24% and 13% lower than those of ordinary concrete at water-to-cementitious materials ratios of 0.4 and 0.5, respectively, while in samples containing silica fume and zeolite, the chloride diffusion coefficient for SSZ0.4 and SSZ0.5 self-compacting samples improved by 18% and 19%, respectively, compared to ordinary concrete samples CSZ0.4 and CSZ0.5.

According to the classification proposed by NT BUILD 492, chloride diffusion coefficient values are categorized into five parts: less than 2, between 2 and 5, between 5 and 10, between 10 and 15, and more than 15, corresponding to

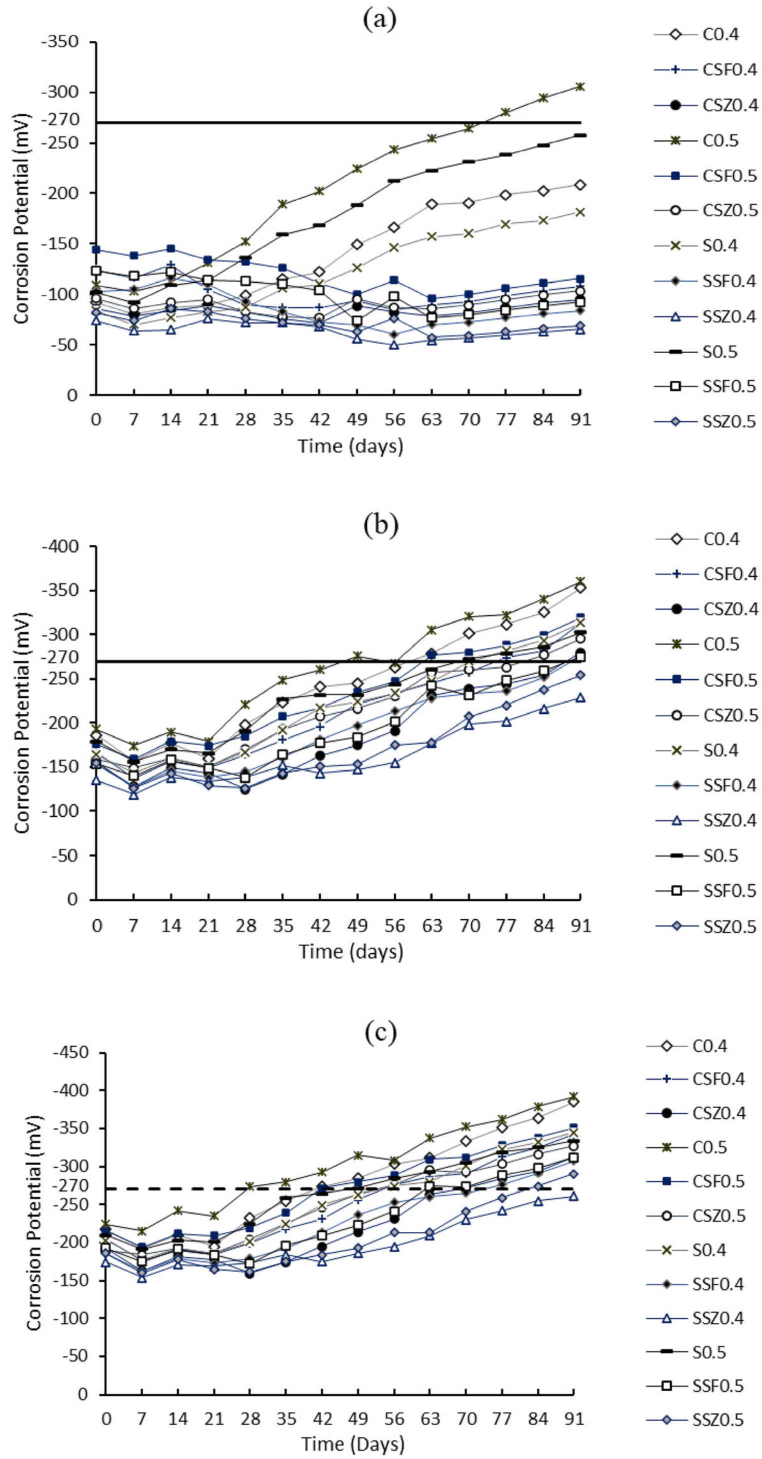


Fig. 11 The electrical potential of rebars in concrete samples. **a** Rebar S1, **b** rebar S4, and **c** rebar S6

the negligible to high range. Based on this ranking, only sample C0.5 falls into the high range, while samples CFZ0.4, SSF0.4, and CSZ0.4 fall into the negligible range, exhibiting the lowest chloride emissions.

3.10 Electric Potential

Figure 11 displays the electrical potential difference between self-compacting and ordinary concrete samples aged between 7 and 91 days for samples S1, S4, and S6. Due to the similarity and proximity of these samples and to avoid repetition, the findings of other samples are not presented. By comparing the corrosion results of the rusted rebar samples with the normal rebar obtained from the factory, it was observed that an increase in the rust condition of the pre-rusted rebar surface led to an increase in corrosion potential. This finding indicates the influence of pre-rusting on steel corrosion when used in concrete, as also mentioned in the research by [28].

When using S1 as reinforcement in concrete, the corrosion rate of the steel is low. Moreover, corrosion is further reduced in self-compacting concrete compared to ordinary concrete, consistent with the research findings [13]. The corrosion reduction in S0.4 and S0.5 samples compared to C0.4 and C0.5 samples at 91 days is 12% and 15%, respectively. An important observation in this graph is the use of SCMs in concrete. When SCMs are incorporated, the potential for corrosion is significantly decreased, and the potential half-cell trend in samples with SCMs differs significantly from those without SCMs. Compared to ordinary concrete, including SCMs in self-compacting concrete improved by 31% and 33% in samples with a water-to-cementitious materials ratio of 0.4 and 0.5, respectively. The findings in [46] support these results. Additionally, the results indicate that the age of corrosion initiation for S1 rebar, when utilized in concrete sample C0.5 (reaching the potential difference value of −270 mV), is 72 days.

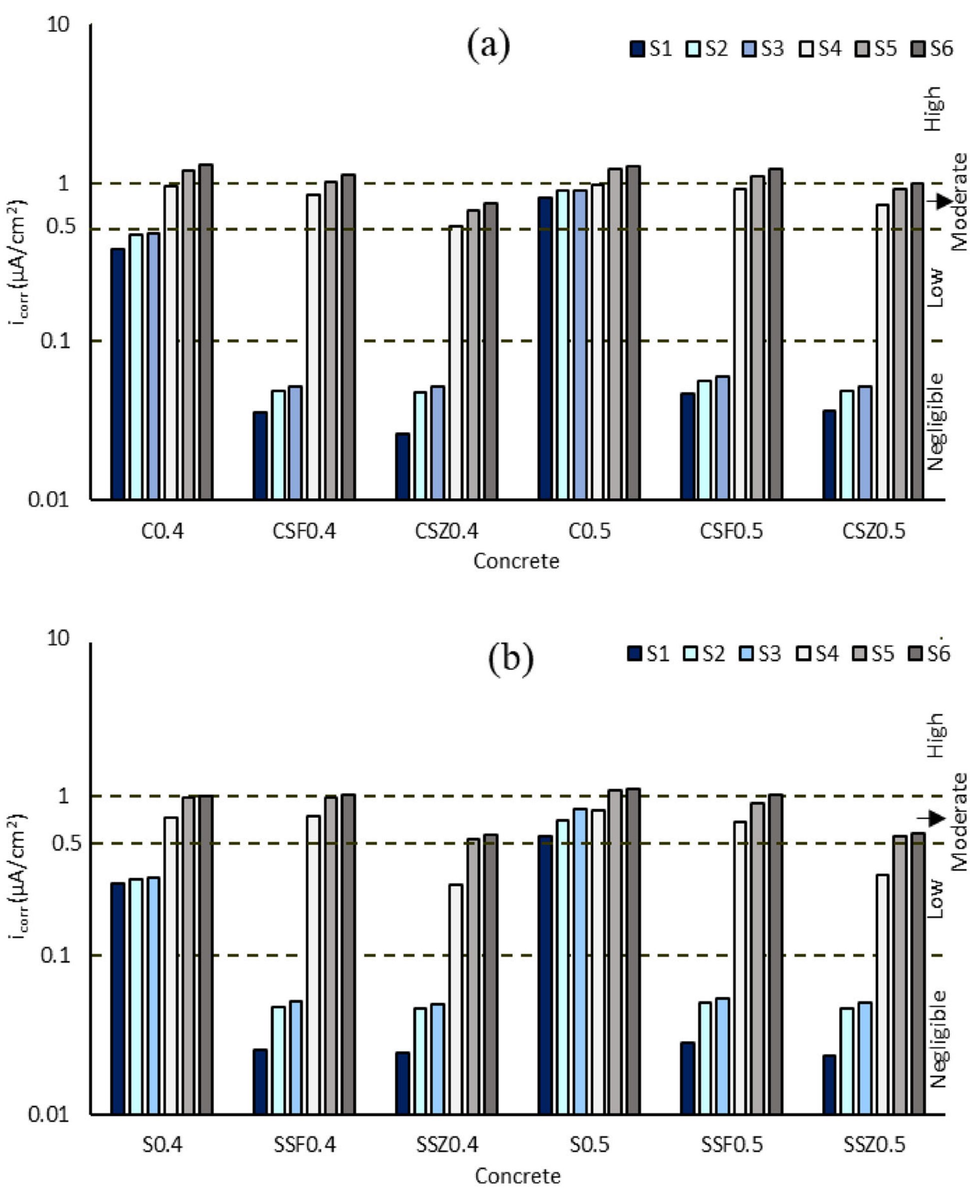


Fig. 12 Corrosion intensity, **a** ordinary concrete samples, **b** SCC samples

When rebars S2 and S3 are used as reinforcement in concrete, the corrosion potential trend is similar to S1. However, the magnitude of corrosion potential in these samples is higher in the S1 sample, and the age of corrosion initiation for the S2 sample in C0.5 concrete is reduced to 66 days, while for the S3 sample in the C0.5 concrete sample, it is lowered to 56 days. Self-compacting concrete samples reduce the amount of corrosion compared to ordinary concrete samples. The lowest corrosion value is observed in the SSZ0.4 sample. Using SCMs in self-compacting concrete improves its performance and reduces the ratio of the water to cementitious material to mitigate corrosion of pre-rusted steel. When using S4 and S5 rebars, the potential corrosion in all concrete specimens increases. As the corrosion of the pre-rusted rebar intensifies, steel corrosion in reinforced concrete also increases. The age of corrosion initiation is lower in these samples, with the quickest corrosion initiation occurring in concrete sample C0.5. The initiation time is 49 days for the S4 sample and 35 days for the S5 sample. Self-compacting concrete and SCMs reduce the corrosion potential of the rebar in these samples.

Furthermore, according to [31], increasing the distance from the sea and storing rebar with plastic covering reduce surface rust on the rebar and, consequently, steel corrosion in reinforced concrete. The most significant change in corrosion potential was observed in the samples containing rebar with artificial rust S6 (Fig. 7c). The age of corrosion initiation in this sample is reduced to 28 days. Due to this rebar's high surface rust level, steel corrosion in reinforced concrete is more pronounced than in other samples. The reduction in corrosion potential is more substantial in samples with SCMs, and the ratio of the water to cementitious material is lower.

When comparing rebar samples embedded in self-compacting concrete to those in ordinary concrete, it is evident that they exhibit reduced corrosion potential regardless of the surface condition. However, it should be emphasized that the impact of self-compacting concrete quality, with the addition of SCMs and a lower water-to-cementitious materials (*W*/*C*) ratio, on steel corrosion in reinforced concrete diminishes as the pre-rusting of the rebar surface increases.

3.11 Intensity of Corrosion

Similar results were obtained in the corrosion intensity test following the potential half-cell test. Figure 12 shows the corrosion intensity of different rebars in ordinary and self-compacting concrete samples at 91 days. The corrosion current intensity in sample C0.5, when utilizing rebar S1, falls within the medium range, while sample S0.5 falls within the low corrosion intensity range. Apart from these two concrete samples, the corrosion intensity in other concrete samples is considered negligible based on the classification by [56]. Nonetheless, in self-compacting samples, the extent of steel corrosion in concrete is lower than that in ordinary concrete samples. By comparing the results of different rebars, it is evident that increased surface rust on the pre-rusted rebar also heightens the intensity of steel corrosion in concrete.

Furthermore, when comparing the influence of concrete quality on corrosion, it is clear that employing higher-quality concrete (self-compacting, low *W*/*C* ratio, and SCMs) minimizes corrosion. The behavior of rebars S2 and S3 is nearly identical to that of rebar S1. However, due to the greater amount of rust on the surfaces of these rebars

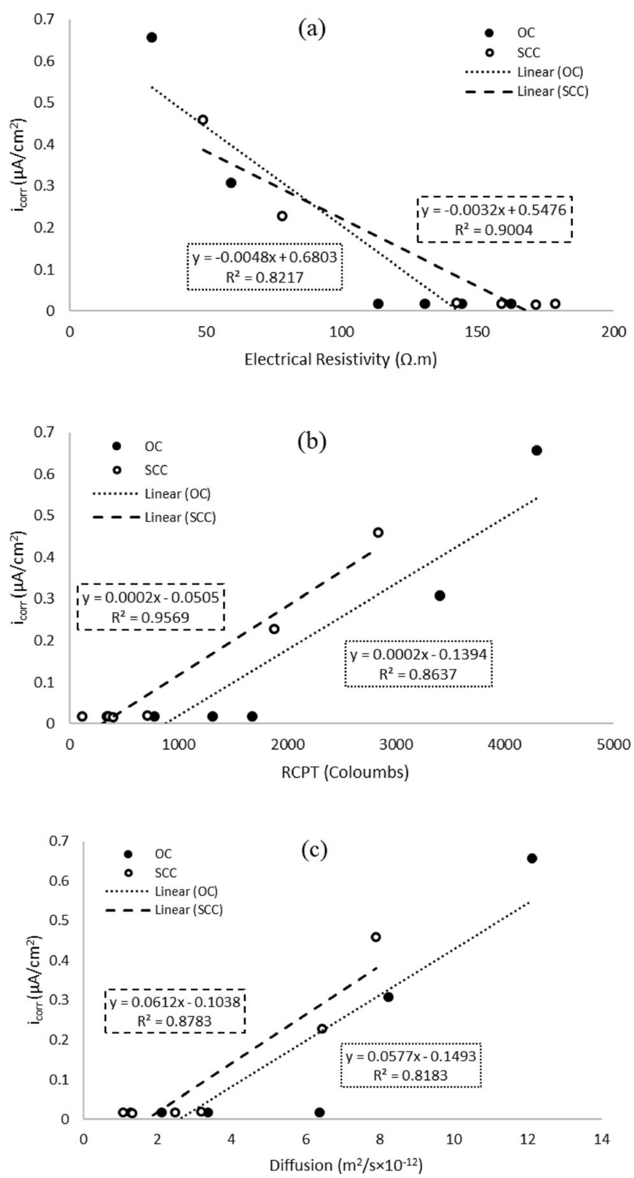


Fig. 13 Relationship between corrosion intensity and **a** electrical resistivity, **b** RCPT, **c** diffusion

Table 5 Relationship between concrete quality tests and corrosion intensity in OC and SCC samples

Experiments and corrosion intensity	In OC	In SCC
Chloride ion diffusion	$y = 0.0577x - 0.1493$ $R^2 = 0.8183$	$y = 0.0612x - 0.1038$ $R^2 = 0.8783$
RCPT	$y = 0.0002x - 0.1394$ $R^2 = 0.8637$	$y = 0.0002x - 0.0505$ $R^2 = 0.9569$
RCMT	$y = 0.0002x - 0.1394$ $R^2 = 0.8637$	$y = 0.0506x - 0.0536$ $R^2 = 0.9799$
Electrical resistivity	$y = -0.0048x + 0.6803$ $R^2 = 0.8217$	$y = -0.0032x + 0.5476$ $R^2 = 0.9004$
Electrical conductivity	$y = 28.991x - 0.2804$ $R^2 = 0.8014$	$y = 29.631x - 0.194$ $R^2 = 0.889$
Compressive strength	$y = -0.0199x + 1.1797$ $R^2 = 0.5693$	$y = -0.0171x + 1.0752$ $R^2 = 0.7056$
Total porosity	$y = 0.067x - 0.4914$ $R^2 = 0.7098$	$y = 0.0947x - 0.2122$ $R^2 = 0.765$
Water absorption	$y = 0.1034x - 0.3047$ $R^2 = 0.4824$	$y = 0.1315x - 0.3084$ $R^2 = 0.6894$

compared to the ordinary rebars supplied by the factory, a higher degree of steel corrosion is observed in the superior concrete. When these rebars are used in self-compacting concrete, the corrosion intensity is lower in ordinary concrete. Among these samples, the C0.5 concrete sample exhibits the highest corrosion intensity. In self-compacting concrete with water-to-cement ratios of 0.5 and 0.4, respectively, a 21% and 36% improvement in corrosion resistance is observed compared to the corresponding concrete samples when utilizing S2 rebar, and a 34% and 12% improvement is observed when using S3 rebar. The SSZ0.4 sample demonstrates the best corrosion resistance when employing these rebars, with corrosion intensities of 0.046 (A/cm^2) in S2 and 0.057 (A/cm^2) in S3. Samples incorporating silica fume SCMs exhibit lower corrosion levels than samples without silica fume at water-to-cementitious materials ratios of 0.4 and 0.5. The integration of SCMs further enhances corrosion resistance.

In the S4 and S5 samples, there is a significant change in corrosion intensity. Consequently, the corrosion intensity of these samples in concrete sample C0.5 increases by 21% and 37%, respectively, compared to rebar S1. Among these rebars, SSZ0.4 exhibits the best performance when used in concrete. When S4 is embedded in concrete, it demonstrates lower corrosion than S5 due to its better surface rust condition. Using the S5 rebar, the maximum and minimum corrosion intensities are 1.21 (μA/cm^2) and 0.54 (μA/cm^2), respectively, whereas, with the S4 rebar, the maximum and minimum corrosion current intensities are 0.96 (μA/cm^2) and 0.028 (μA/cm^2). In these samples, self-compacting concrete outperforms ordinary concrete. Compared to ordinary concrete, the corrosion intensity value in self-compacting concrete samples with water-to-cementitious materials ratios of 0.4 and 0.5 is reduced by 15% to 23% when utilizing the S4 rebar and 10% to 18% when utilizing the S5 rebar, respectively.

The rebar sample S6 exhibits the highest intensity of corrosion. When used in C0.5 concrete, the corrosion current intensity of this sample reaches 1.28 (μA/cm^2) at 91 days, which is the upper limit of the corrosion intensity diagram. In the best-case scenario, when this sample is used in SSZ0.4 concrete, the corrosion intensity is 0.58 (μA/cm^2), falling within the moderate range. In all ordinary concrete specimens except CSZ0.4, the corrosion intensity of this rebar falls within the high range. However, the situation improves in self-compacting concrete, and the corrosion intensity decreases. Based on the results, the influence of self-compacting concrete performance in mitigating steel corrosion in reinforced concrete is evident in all rebar samples.

Table 6 The effect of SCC quality on corrosion of different rebars in concrete

Surface rust	i_{corr} (μA/cm^2) in the sample C0.5	i_{corr} (μA/cm^2) in the sample SSZ0.4	Impact rate (%)
S1	0.80	0.02	97.6
S2	0.57	0.04	93.4
S3	0.74	0.07	90.6
S4	0.97	0.28	71.4
S5	1.21	0.54	55.1
S6	1.28	0.57	55.6

3.12 Relation of Different Parameters of Concrete Quality With the Intensity of Corrosion

The relationship between different concrete performance tests and the corrosion intensity of normal rebar received from the factory was investigated. Since factors other than concrete quality, such as the condition of the rebar surface, can also influence the corrosion intensity in other rebars, the results of ordinary rebar S1 were used to minimize side effects and solely focus on comparing the effect of concrete type on the intensity of steel corrosion. The evaluation indicates that the results of electrical resistance, electrical conductivity, RCPT, RCMT, and diffusion tests are closely related to the corrosion current intensity. These tests are associated with the penetration and diffusion properties of chloride ions in concrete. Since corrosion in the Persian Gulf region is mainly chloride induced, it is predictable that there would be a relationship between the results of these tests and the corrosion intensity rate. Figure 13 shows the relationship between electrical resistance tests, RCPT, and diffusion with the rate of corrosion intensity of steel in reinforced concrete when using S1 rebar, measured based on the type of self-compacting concrete. Table 5 presents the data from correlating other tests with the current intensity of corrosion. The lack of a significant correlation between mechanical parameters (compressive strength, water absorption volume, and total porosity) and corrosion rate may suggest that the free chloride required to initiate corrosion is supplied from within the structure (pre-rusted rebar). Therefore, steel corrosion in reinforced concrete is primarily influenced by the electrochemical properties of concrete.

The relationship between the electrical resistance test and corrosion intensity (Fig. 13a) in self-compacting and ordinary concrete samples reveals that the correlation between the electrical resistance test and corrosion current intensity is 90% for self-compacting concrete samples. When ordinary concrete is used, this correlation decreases to 82%. In Fig. 13b, which illustrates the correlation between RCPT test results and the rate of corrosion intensity, self-compacting concrete specimens exhibit a 96% correlation, while ordinary concrete specimens show an 86% correlation. The correlation between the diffusion test in self-compacting concrete and the rate of corrosion intensity (Fig. 13c) is 87%, higher than the correlation results observed in ordinary concrete. The relationship between other tests and the rate of corrosion intensity in Table 5 confirms the stronger association between the results of self-compacting concrete and the rate of corrosion intensity. Based on the evaluation results, it is evident that self-compacting concrete has a more significant relationship in determining the intensity of corrosion in almost all tests, with higher correlation values compared to ordinary concrete samples. Consequently, employing self-compacting concrete can better control the extent of steel corrosion in reinforced concrete.

3.13 Comparison of the Effect of Self-Compacting Concrete Performance on Corrosion of Ordinary and Pre-Rusted Rebar

Table 6 summarizes the performance of self-compacting and ordinary concrete on the corrosion intensity of different rebars in reinforced concrete at 91 days. According to the results of concrete quality tests, the SSZ0.4 sample outperformed all other samples, while sample C0.5 had the lowest rating. Consequently, these two samples were selected as representing the best and worst concrete quality, respectively, to assess the impact of concrete quality on the corrosion of various rebars. The findings in the table indicate that when rebar S1 is used to reinforce concrete, corrosion is reduced by 97% in SSZ0.4 (self-compacting concrete) compared to C0.5 (ordinary concrete). This reduction ranges from 93 to 55% in samples S2–S6. When different rebars are employed, the influence of concrete quality on steel corrosion reveals that as the amount of rust on the rebar surface increases, the effect of concrete quality on corrosion intensity diminishes. However, concrete quality still affects the severity of corrosion. This finding emphasizes that, in addition to concrete quality, the condition of rebar corrosion in reinforced concrete plays a significant role. Therefore, employing high-quality self-compacting concrete can significantly reduce steel corrosion in reinforced concrete. However, it is crucial to closely monitor and examine the condition of the rebar surface before manufacturing reinforced concrete samples.

4 Conclusions

This study aimed to investigate the impact of self-compacting concrete quality on corrosion reduction in reinforced concrete when pre-rusted rebar is used. The key findings of this investigation are summarized below:

1. When pre-rusted rebar is employed in reinforced concrete, the intensity of steel corrosion is closely related to tests measuring the chloride diffusion coefficient, rapid chloride permeability, and rapid chloride migration. This relationship is 10–15% stronger when self-compacting concrete is utilized than regular concrete.

2. Incorporating supplementary cement materials and reducing the ratio of the water to cementitious material in self-compacting concrete resulted in a 13–48% greater reduction in corrosion risk compared to similar samples in ordinary concrete.
3. Properties associated with chloride diffusion in concrete, such as the chloride ion diffusion coefficient, chloride ion accelerated penetration, and chloride ion migration coefficient, strongly influenced the corrosion of pre-rusted steel in reinforced concrete. In these aspects, self-compacting concrete outperformed ordinary concrete, leading to lower corrosion levels in rebars with different degrees of pre-rust.
4. Self-compacting concrete exhibited superior mechanical properties and durability parameters compared to ordinary concrete.
5. Apart from concrete quality, the condition of the rebar surface in terms of rust also impacts the corrosion of pre-rusted rebar in reinforced concrete. Factors such as proximity to the sea and proper storage methods for rebar significantly influence the corrosion of the rebar surface and, consequently, steel corrosion in reinforced concrete.

Author contributions All the authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by M. Khoshroo and P. Ghoddousi. The first draft of the manuscript was written by M. Khoshroo; all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

Declarations

Ethical approval The authors state that the research was conducted according to ethical standards. This manuscript has been prepared by the contribution of all the authors, it is the original authors work, it has not been published before, it has been solely submitted to this journal, and if accepted, it will not be submitted to any other journal in any language. The authors state that this article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Tahri W, Hu X, Shi C, Zhang Z (2021) Review on corrosion of steel reinforcement in alkali-activated concretes in chloride-containing environments. Constr Build Mater 293:123484. https://doi.org/10.1016/j.conbuildmat.2021.123484
2. Michel A, Sørensen HE, Geiker MR (2021) 5 years of in situ reinforcement corrosion monitoring in the splash and submerged zone of a cracked concrete element. Constr Build Mater 285:122923. https://doi.org/10.1016/j.conbuildmat.2021.122923
3. Holland R, Kurtis K, Kahn L (2016) Effect of different concrete materials on the corrosion of the embedded reinforcing steel. In: Corrosion of steel in concrete structures, pp 131–147. https://doi.org/10.1016/B978-1-78242-381-2.00007-9
4. Rong C, Yingshuang H, Miao Y, Wenyu L, Lufeng Y, Aditya K (2020) Skin effect of chloride ingress in marine concrete: a review on the convection zone. Constr Build Mater 262:120566. https://doi.org/10.1016/j.conbuildmat.2020.120566
5. Shi C, Hu X, Wang X, Wu Z, Schutter GD (2017) Effects of chloride ion binding on microstructure of cement pastes. J Mater Civil Eng 29(1):04016183. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001707
6. Ranjbar MM, Madandoust R, Mousavi SY, Yosefi S (2013) Effects of natural zeolite on the fresh and hardened properties of self-compacted concrete. Constr Build Mater 47:806–813. https://doi.org/10.1016/j.conbuildmat.2013.05.097
7. Nosratzehi N, Miri M (2020) Experimental investigation on chloride diffusion coefficient of self-compacting concrete in the Oman sea. Period Polytech Civil Eng 64(3):647–657. https://doi.org/10.3311/PPci.15335
8. Calado C, Camões A, Monteiro E, Helene P, Barkokébas B (2015) Durability indicators comparison for SCC and CC in tropical coastal environments. Materials 8(4):1459–1481. https://doi.org/10.3390/ma8041459
9. Kanellopoulos A, Petrou MF, Ioannou I (2012) Durability performance of self-compacting concrete. Constr Build Mater 37:320–325. https://doi.org/10.1016/j.conbuildmat.2012.07.049
10. Zong L, Zhang SP, Liang PX (2011) Experiment study on the durability of dry-mixing self-compacting concrete. In: Advanced materials research, pp 493–496. https://doi.org/10.4028/www.scientific.net/AMR.250-253.493
11. Ryan PC, O'Connor A (2016) Comparing the durability of self-compacting concretes and conventionally vibrated concretes in chloride rich environments. Constr Build Mater 120:504–513. https://doi.org/10.1016/j.conbuildmat.2016.04.089
12. Shadkam HR, Dadsetan S, Tadayon M, Sanchez LF, Zakeri JA (2017) An investigation of the effects of limestone powder and viscosity modifying agent in durability related parameters of self-consolidating concrete (SCC). Constr Build Mater 156:152–160. https://doi.org/10.1016/j.conbuildmat.2017.08.165
13. Jain S, Pradhan B (2019) Corrosion performance of steel in self-compacting concrete exposed to chloride environment. In: Recent advances in structural engineering, vol 2, pp 549–558. Springer. https://doi.org/10.1007/978-981-13-0365-4_47
14. Jain S, Pradhan B (2020) Fresh, mechanical, and corrosion performance of self-compacting concrete in the presence of chloride ions. Constr Build Mater 247:118517. https://doi.org/10.1016/j.conbuildmat.2020.118517
15. Dinakar P, Babu K, Santhanam M (2009) Corrosion resistance performance of high-volume fly-ash self-compacting concretes. Mag Concr Res 61(2):77–85. https://doi.org/10.1680/macr.2006.00016
16. Ahmad S, Adekunle SK, Maslehuddin M, Azad AK (2014) Properties of self-consolidating concrete made utilizing alternative mineral fillers. Constr Build Mater 68:268–276. https://doi.org/10.1016/j.conbuildmat.2014.06.096
17. Al-Akhras N, Aleghnimat R (2020) Evaluating corrosion deterioration in self-compacted reinforced concrete beams and prisms using different tests. Constr Build Mater 256:119347. https://doi.org/10.1016/j.conbuildmat.2020.119347
18. Wasim M, Ngo TD, Abid M (2020) Investigation of long-term corrosion resistance of reinforced concrete structures constructed with various types of concretes in marine and various climate environments. Constr Build Mater 237:117701. https://doi.org/10.1016/j.conbuildmat.2019.117701
19. Hassan A, Hossain K, Lachemi M (2009) Corrosion resistance of self-consolidating concrete in full-scale reinforced beams. Cement Concr Compos 31(1):29–38. https://doi.org/10.1016/j.cemconcomp.2008.10.005

20. Mohammed AN, Johari MAM, Zeyad AM, Tayeh BA, Yusuf MO (2014) Improving the engineering and fluid transport properties of ultra-high strength concrete utilizing ultrafine palm oil fuel ash. J Adv Concr Technol 12(4):127–137. https://doi.org/10.3151/jact.12.127
21. Zeyad AM, Almalki A (2021) Role of particle size of natural pozzolanic materials of volcanic pumice: flow properties, strength, and permeability. Arab J Geosci 14:1–11. https://doi.org/10.1007/s12517-020-06443-y
22. Zeyad AM, Johari MAM, Abutaleb A, Tayeh BA (2021) The effect of steam curing regimes on the chloride resistance and pore size of high-strength green concrete. Constr Build Mater 280:122409. https://doi.org/10.1016/j.conbuildmat.2021.122409
23. Zeyad AM, Johari MM, Tayeh BA, Yusuf MO (2016) Efficiency of treated and untreated palm oil fuel ash as a supplementary binder on engineering and fluid transport properties of high-strength concrete. Constr Build Mater 125:1066–1079. https://doi.org/10.1016/j.conbuildmat.2016.08.065
24. Elbasri OM, Nser S, Shubaili M, Abdullah GM, Zeyad AM (2022) Performance of self-compacting concrete incorporating wastepaper sludge ash and pulverized fuel ash as partial substitutes. Case Stud Constr Mater 17:01459. https://doi.org/10.1016/j.cscm.2022.e01459
25. Amin M, Zeyad AM, Tayeh BA, Agwa IS (2023) Effect of glass powder on high-strength self-compacting concrete durability. Key Eng Mater 945:117–127. https://doi.org/10.4028/p-w4tcjx
26. Al-Tayyib A, Khan MS, Allam I, Al-Mana A (1990) Corrosion behavior of pre-rusted rebars after placement in concrete. Cem Concr Res 20(6):955–960. https://doi.org/10.1016/0008-8846(90)90059-7
27. Burtuujin G, Son D, Jang I, Yi C, Lee H (2020) Corrosion behavior of pre-rusted rebars in cement mortar exposed to harsh environments. Appl Sci 10(23):8705. https://doi.org/10.3390/app10238705
28. González J, Miranda J, Otero E, Feliu S (2007) Effect of electrochemically reactive rust layers on the corrosion of steel in a Ca (OH) 2 solution. Corros Sci 49(2):436–448. https://doi.org/10.1016/j.corsci.2006.04.014
29. Martinez-Echevarria M, Lopez-Alonso M, Romero DC, Montero JR (2018) Influence of the previous state of corrosion of rebars in predicting the service life of reinforced concrete structures. Constr Build Mater 188:915–923. https://doi.org/10.1016/j.conbuildmat.2018.08.173
30. Maslehuddin M, Al-Zahrani M, Al-Dulaijan S, Rehman S, Ahsan S (2002) Effect of steel manufacturing process and atmospheric corrosion on the corrosion-resistance of steel bars in concrete. Cement Concr Compos 24(1):151–158. https://doi.org/10.1016/S0958-9465(01)00035-X
31. Song D, Yang F, Guo M, Zhao S, Hao J, Chen Z et al (2019) Surface modification of rusted rebar and enhanced passivation/anticorrosion performance in simulated concrete pore solutions with different alkalinity. Metals 9(10):1050. https://doi.org/10.3390/met9101050
32. Meira G, Andrade C, Vilar E, Nery K (2014) Analysis of chloride threshold from laboratory and field experiments in marine atmosphere zone. Constr Build Mater 55:289–298. https://doi.org/10.1016/j.conbuildmat.2014.01.052
33. Ye H, Fu C, Jin N, Jin X (2018) Performance of reinforced concrete beams corroded under sustained service loads: a comparative study of two accelerated corrosion techniques. Constr Build Mater 162:286–297. https://doi.org/10.1016/j.conbuildmat.2017.10.108
34. Hassan AA, Lachemi M, Hossain KM (2012) Effect of metakaolin and silica fume on the durability of self-consolidating concrete. Cement Concr Compos 34(6):801–807. https://doi.org/10.1016/j.cemconcomp.2012.02.013
35. Khoshroo M, Javid AAS, Katebi A (2018) Effects of micro-nano bubble water and binary mineral admixtures on the mechanical and durability properties of concrete. Constr Build Mater 164:371–385. https://doi.org/10.1016/j.conbuildmat.2017.12.225
36. Radhi MS, Hassan MS, Gorgis IN (2018) Experimental comparability among different accelerated reinforced steel concrete corrosion methods. Int J Eng Technol 7(4.20): 209. https://doi.org/10.14419/ijet.v7i4.20.25928
37. Koehler EP, Fowler DW (2004) Development of a portable rheometer for fresh portland cement concrete. http://hdl.handle.net/2152/35338
38. McCarter WJ, Starrs G, Kandasami S, Jones R, Chrisp M (2009) Electrode configurations for resistivity measurements on concrete. ACI Mater J 106(3):258–264
39. Khoshroo M, Ghoddousi P (2023) Minimizing the negative impacts of rebar stored in the Persian Gulf on reinforced concrete corrosion. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2022.129749
40. Lu C, Yang H, Mei G (2015) Relationship between slump flow and rheological properties of self-compacting concrete with silica fume and its permeability. Constr Build Mater 75:157–162. https://doi.org/10.1016/j.conbuildmat.2014.08.038
41. Hajforoush M, Madandoust R, Kazemi M (2019) Effects of simultaneous utilization of natural zeolite and magnetic water on engineering properties of self-compacting concrete. Asian J Civil Eng 20(2):289–300. https://doi.org/10.1007/s42107-018-00106-w
42. Khoshroo M, Javid AAS, Katebi A (2018) Effect of chloride treatment curing condition on the mechanical properties and durability of concrete containing zeolite and micro-nano-bubble water. Constr Build Mater 177:417–427. https://doi.org/10.1016/j.conbuildmat.2018.05.086
43. Alaghebandian N, Mirvalad S, Javid AAS (2020) Durability of self-consolidating concrete and mortar mixtures containing ternary and quaternary cement blends exposed to simulated marine environment. Constr Build Mater 259:119767. https://doi.org/10.1016/j.conbuildmat.2020.119767
44. GuptA S (2014) Application of silica fume and nanosilica in cement and concrete—a review. J Today Ideas Tom Technol. https://doi.org/10.15415/jotitt.2013.12006
45. Nili M, Ehsani A (2015) Investigating the effect of the cement paste and transition zone on strength development of concrete containing nanosilica and silica fume. Mater Des 75:174–183. https://doi.org/10.1016/j.matdes.2015.03.024
46. Naderi M, Kaboudan A, Kargarfard K (2021) Studying the compressive strength, permeability and reinforcement corrosion of concrete samples containing silica fume, fly ash and zeolite. J Struct Constr Eng 8(2): 25–43. https://doi.org/10.22065/jsce.2019.154574.1697
47. Ghoddousi P, Saadabadi LA (2018) Pore structure indicators of chloride transport in metakaolin and silica fume self-compacting concrete. Int J Civil Eng 16(5):583–592. https://doi.org/10.1007/s40999-017-0164-0
48. Moghadam MA, Izadifard RA (2019) Experimental investigation on the effect of silica fume and zeolite on mechanical and durability properties of concrete at high temperatures. SN Appl Sci 1(7):1–11. https://doi.org/10.1007/s42452-019-0739-2
49. Malakooti A (2004) Investigation of concrete electrical resistivity as a performance based test. Cement Concr Res 34(3): 537–545. https://doi.org/10.13140/RG.2.2.28525.69603
50. Shi C (2004) Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results. Cem Concr Res 34(3):537–545. https://doi.org/10.1016/j.cemconres.2003.09.007
51. Meddah MS, Ismail MA, El-Gamal S, Fitriani H (2018) Performances evaluation of binary concrete designed with silica fume

and metakaolin. Constr Build Mater 166:400–412. https://doi.org/10.1016/j.conbuildmat.2018.01.138

52. Revilla-Cuesta V, Skaf M, Espinosa A, Ortega-López V (2021) Multi-criteria feasibility of real use of self-compacting concrete with sustainable aggregate, binder and powder. J Clean Prod 325:129327. https://doi.org/10.1016/j.jclepro.2021.129327
53. Ramezanianpour AA, Kazemian A, Sarvari M, Ahmadi B (2013) Use of natural zeolite to produce self-consolidating concrete with low Portland cement content and high durability. J Mater Civ Eng 25(5):589–596. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000621
54. Pontes J, Bogas J, Real S, André Silva A (2021) The rapid chloride migration test in assessing the chloride penetration resistance of normal and lightweight concrete. Appl Sci. https://doi.org/10.3390/app11167251
55. Valipour M, Pargar F, Shekarchi M, Khani S (2013) Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: a laboratory study. Constr Build Mater 41:879–888. https://doi.org/10.1016/j.conbuildmat.2012.11.054
56. Novak P, Mala R, Joska L (2001) Influence of pre-rusting on steel corrosion in concrete. Cem Concr Res 31(4):589–593. https://doi.org/10.1016/S0008-8846(01)00459-8