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RESEARCH PAPER

Investigation on Chloride-Induced Corrosion Reduction Strategies for Offshore Reinforced Concrete Structures

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Abstract

The corrosion of reinforcement by chloride ions is a significant issue for reinforced concrete (RC) structures, which causes instability and loss of strength of the structure. In this study, the efficacy of various strategies for limiting the effects of chloride-induced corrosion on offshore RC structures was investigated experimentally through a series of experimental tests, including uniaxial compression test, half-cell potential test, and chloride ion penetration test. The tests have been conducted on concrete cube specimens with water/cement (w/c) ratios of 0.38, 0.45, and 0.50, which, for each w/c, the effect of normal cement (control specimens), engineered cementitious composite, self-compacting concrete (SCC), migration corrosion inhibitor (MCI), and microsilica (MS) were separately considered. The compressive strength of the specimens was obtained by uniaxial compression test at 7 and 28 days. Furthermore, to simulate wetting–drying cycles in marine environment, their corresponding 28 days cured specimens were exposed to the marine tidal zone at Technology and Durability Research Centre of Amir Kabir University, located at Bandar-e-Imam Khomeini, Iran, for 16 months and then were tested by half-cell potential and chloride ion penetration tests. The results revealed that, among all the specimens, the specimens with MCI and SCC achieved the highest and lowest compressive strength. In addition, the quantity of chloride ions that penetrate to the specimens indicates a low-risk corrosion for the specimens with MS and MCI and high-risk corrosion for the specimens with SCC. Moreover, it was concluded that using MCI was the most successful strategy for preventing reinforcement corrosion in maritime concrete structures.

Keywords Offshore concrete structure · Reinforcement corrosion · Durability · Chloride-induced corrosion · Corrosion measurement

1 Introduction

The most common cause of premature failure in reinforced concrete structures is corrosion of the steel reinforcement that was induced by chloride (Goyal et al. 2021). Corrosion can induce failure of the concrete. Because of this, the life of the concrete is shorter, which results in enormous losses (Moradian et al. 2012). According to Shekarchi et al., when chloride is present in the air for an extended period of time, it has a tendency to seep into the pores of concrete. This can cause the rebars that are used in reinforced concrete to rust in hostile situations (Shekarchi et al. 2011). As soon as the chloride concentration reaches the critical level, the passive oxide layer that covers the steel rebars begins to erode, which, in turn, causes the steel to corrode. This cycle continues until the steel is completely corroded. Because of the alkalinity of the concrete, steel that is embedded in it is typically protected from corrosion. This is due to the establishment of a passive layer, which was made possible by the alkalinity of the concrete. According to Nygaard and Geiker (2005), the loss of this protective layer, which is known as DE passivation, is caused by the presence of chlorides in the environment (Nygaard and Geiker 2005). It is impossible for corrosion to start until this layer is first compromised. Reinforcing corrosion can be avoided to some extent by utilizing concrete of a high quality and low permeability. Reinforcing steel corrosion can be prevented and controlled by selecting corrosion prevention measures in the case that severe environmental conditions are present (Abedini and Zhang 2022). This is a suitable solution for preventing the corrosion of

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reinforcing steel. In recent years, a number of various techniques and processes for preventing corrosion caused by chloride exposure have been presented. These strategies and procedures aim to protect against corrosion in a variety of different ways. According to Morris and Vazquez (2002a, b), their goal has been to manufacture concrete structures that are not only longer lasting but also more resistant (Morris and Vazquez 2002a, b).

According to Morris and Vazquez (2002a, b), the corrosion behavior of reinforcing steel bars, often known as rebars, was evaluated in four distinct concrete mix designs throughout the testing. These blueprints were exposed to a variety of conditions with varied intensities. In order to examine the efficacy of a surface-applied migrating corrosion inhibitor that was generated from an alkylamino alcohol, its influence on a sample of concrete was put through a series of tests. There are two distinct amounts of chloride, two distinct kinds of exposure, and two distinct proportions of water to cement (w/c).

The effectiveness of the inhibitors was evaluated using a number of different metrics over the course of about 1000 days. Some of these measures were corrosion potential, corrosion current, and electrical resistance. According to Morris and Vazquez's research (2002a, b), the findings demonstrate that a corrosion inhibitor has the ability to lessen the rate at which concrete deteriorates in a marine setting (Morris and Vazquez 2002a, b). Malik and colleagues (2004) have carried out research in order to investigate the effectiveness of MCIs. The experiments consisted of either submerging the specimens in solutions of 5% NaCl in open saltwater or exposing the specimens to high tide in a splash zone for durations of time ranging from 6 to 12 months. The laboratory testing was conducted in a controlled environment. According to Malik et al. (2004), ocular inspection revealed either no corrosion at all or very little corrosion after 19 months of exposure (Malik et al. 2004). The objective of the study that Pan et al. (2020) carried out was to investigate potential solutions to issues with the long-term durability of concrete structures, namely, those issues that are caused by chloride-induced corrosion. In order to investigate the anticorrosion performance of migrating corrosion inhibitor (MCI-0), electrochemical methods were utilized. Additionally, the axial compression and electric flux of high-performance concrete with various mix formulations that incorporated inhibitor, nano-components, and functional components were tested. According to the findings, the resistance of the steel rebar to corrosion has been greatly improved (Pan et al. 2020). Zheng et al. (2012) investigated the impact that a surface-applied corrosion inhibitor had on the durability of concrete by employing three different types of tests: the capillary water absorption test, the chloride penetration test, and the accelerated carbonation test. According to the findings, applying the inhibitor to the surface of the hardened concrete led to improvements in the material's resistance to water, chloride, and carbonation, which led to an increase in its overall durability. Zheng, Li, and his colleagues conducted research in 2012 on the effect of a surface-applied corrosion. According to Zheng et al. (2012) research, the effectiveness of the inhibitor that was applied decreased over time as the ratio of water to cement grew and as the density of the concrete decreased (Zheng et al. 2012).

In 2021, research led by Goyal, Ganjian, and others found that chloride-induced corrosion of steel reinforcement is the primary reason for the early failure of reinforced concrete structures. This was discovered as a result of the work that was done. An analysis into the inhibitor efficiency of six main commercial migratory corrosion inhibitors for reinforced concrete that is available in the UK was carried out by conducting electrochemical research and taking permeability measurements. This investigation was carried out in the UK. The purpose of this study was to identify which inhibitor is the most efficient at preventing the corrosion of steel in concrete that is exposed to high concentrations of chloride. The research indicates that these compounds perform exceptionally well as efficient inhibitors for reinforced concrete projects. Vedalakshmi et al. (2009) evaluated the migration efficiency of an amino alcohol-based migrating corrosion inhibitor through hardened concrete of two different strengths (20 and 30 MPa) and two different thicknesses (25 and 40 mm). They did this by using a diffusion test cell arrangement. According to the findings of the researchers, the MCR of steel in the presence of MCI is significantly lower than that of bare steel by a factor of twenty (Vedalakshmi et al. 2009).

According to Eskandari-Naddaf and Ziaei-Nia (2018), the research investigated how the corrosion rate of steel in C-525 cement concrete altered when nano-silica was added rather than microsilica. Specifically, the researchers looked at how the corrosion rate changed when nano-silica was applied. This activity took place in an atmosphere that was highly acidic. In particular, the researchers were interested in determining how this replacement impacted the rate of corrosion. In order to achieve this objective, seven distinct series of cylindrical corrosion samples were fabricated and subjected to an extensive battery of electrochemical tests. The corrosion potential, linear polarization, impedance spectroscopy, and Tafel polarization tests were some of the examinations that were carried out. According to the research conducted by Eskandari-Naddaf and Ziaei-Nia (2018), the findings indicated that a combination of 1.6% nano-silica and 9.4% microsilica should be used in order to achieve the most acceptable cost when taking into consideration the improved usable life of concrete buildings and the optimal reduction in the rate of corrosion of concrete (Eskandari-Naddaf and Ziaei-Nia 2018). In the research that was conducted in 2008 by Muralidharan, Parande, and others, the authors investigated how the presence of microsilica influenced both the concrete's resistance to corrosion and its strength. The results of all of these trials showed that increasing the amount of microsilica added to conventional Portland cement by up to 8 percent by weight increased the cement's resistance to corrosion. The incorporation of microsilica into concrete boosts the material's resistance to stress and helps it keep its structural integrity over time. According to other reports, the integration of microsilica leads to a significant reduction in permeability (Muralidharan et al. 2008). Baltazar-Zamora et al. examined the effect that microsilica and fly ash have on the rate of corrosion in concrete for their research (Baltazar-Zamora et al. 2019). Monitoring of corrosion based on potential (Ecorr) corrosion was carried out in line with the standard set by ASTM C876 in order to accomplish this objective. Because the critical chloride threshold was not met, the application of microsilica resulted in a reduction in the porosity of the concrete, which, in turn, had the effect of decreasing the permeability of chloride ions. The findings demonstrated that the utilization of 20% microsilica and fly ash in the reinforced concrete in the first 105 days resulted in a 10% reduction in corrosion, which was maintained up to 365 days later, resulting in an improvement in the corrosion function of the concrete. This suggests that the microsilica, which reduced the porosity of the concrete, was responsible for the decrease in the permeability of chloride ions. In the meantime, three specimens that were generated without the addition of microsilica or fly ash demonstrated severe corrosion (more than 3 A/cm^2) for an entire year (Baltazar-Zamora et al. 2019). The findings of a study conducted by Moffat et al. (2018) indicate that, when subjected to an offshore environment for the same amount of time and under the same conditions, the performance of concrete that contained fly ash and microsilica was able to reduce the depth of chloride penetration from 90 to 40 mm (Moffatt and Thomas 2018).

Berke and Hicks (1992) did research on the entrance of chloride into concrete using the FICK diffusion equation for concrete that had been fully cured. This equation was used for the purpose of studying the phenomenon. According to the findings (Berke and Hicks 1992), a reduction in the quantity of chloride penetration can be achieved by decreasing the ratio of water to cement, increasing the concrete cover over the steel, and introducing microsilica into the mixture of concrete. Dousti et al. (2011), several critical parameters, such as the w/c ratio, the microsilica replacement, and the influence of chloride concentration on chloride binding, were investigated in order to get insight into the distribution of free and bound chloride ions after a protracted exposure. This was done in order to gain knowledge about the distribution of free and bound chloride ions. According to the results of the research conducted by Dousti et al. (2011), the quantity of chloride that can be bound by microsilica reduces as the w/c ratio and chloride concentration increase, while the total amount of chloride that can be bound increases (Dousti 2011).

Research on the engineered cement composite was carried out by Kewalramani et al. (2017). According to the findings, various composites, in addition to having the ability to repair ordinary concrete, have imparted high ductility, high tensile strength, a low permeability coefficient, and higher resistance to steel corrosion when compared to conventional concrete in a typical hot, arid coastal region experiencing an extremely harsh climate (Kewalramani et al. 2017). This was demonstrated by the fact that the various composites also had the ability to repair ordinary concrete. We investigated the possibility of using limestone powder (LSP) and high-volume fly ash as partial replacements for silica sand and Portland cement. Additionally, they conducted quick chloride ion penetration tests and examined their effects on the ECC's durability.

Turk et al. (2022) revealed that the replacement of LSP with SS improved both the mechanical strengths and the durability characteristics of ECC. This was due to the refined pore size distribution that was induced by the action of microfiller, as well as the resistance to the freezing cycle and the penetration of chloride ions in ECC. In addition, the results demonstrated that ECC was resistant to the freezing cycle. Because of the influence of the microfillers, the pore size distribution was improved, which made these advances possible (Turk et al. 2022).

Experimental investigations were conducted to evaluate the durability performance of engineered cementitious composite and normal concrete, as stated by Komara et al. (2020). These studies involved the use of controlled laboratory conditions. In order to accomplish this objective, direct measurements on sorptivity, water absorption, and rapid chloride penetration were performed on both ECC and ordinary concrete. These tests were carried out in order to compare the two types of concrete. The results of these investigations indicate that the inherent low permeability features of ECC give exceptional durability performance. This is highlighted by the fact that these properties have been highlighted. This is especially true in regard to the enhancement of sorptivity rate and water absorption, both of which are twice as high as those of standard concrete, suggesting the very dense capillary pore microstructure that has been incorporated. It has also been found that the amount of chloride that is present on the surface of ECC is fifty percent lower than what is found on conventional concrete (Komara et al. 2020). This finding was made possible by the use of ECC.

The purpose of this research is to assess the efficacy of several strategies for preventing chloride corrosion in maritime environments and to compare those strategies with one another. If we find that any of the compounds can prevent corrosion more effectively than the control circumstances, we will seriously consider employing that compound as a chemical. Employers, practitioners, and contractors can instantly use the findings of this research to make educated judgments about which method is best for preventing corrosion, restoring concrete, and securing it from further damage. This research was funded by the National Concrete Repair Institute (NCRI).

2 Modified Chloride Diffusion Model for Offshore Structures

The most detrimental thing that may occur to concrete structures is corrosion induced by chloride. This is one of the reasons why concrete is so durable (Abedini and Zhang 2021). When maritime environments come into contact with reinforced concrete structures, this phenomenon occurs. According to Valipour et al. (2013) research, chloride-induced corrosion of reinforcing steel is the most significant factor that reduces the longevity of RC structures seen in offshore constructions. Because of this, it is of the utmost importance to do study on the resistance of concrete to the penetrating effects of chloride ions. Both the beginning of the process of corrosion and the surface of the corrosion go through a progression of three stages. The first stage is called the diffusion stage, and it is related with the process of chloride ions dispersing on the surfaces of the reinforcement. The second stage of the problem is associated with the advancement of the problem from the time the corrosion initially started until the concrete started to fracture, and the third stage is associated with the deterioration of the situation (Valipour et al. 2013). The amount of chloride ions in concrete that is a result of corrosion is a function of both the depth of the concrete and the amount of time that has passed, in accordance with Fick's law and a one-dimensional solution that was obtained from existing models. Fick's rule is widely utilized in today's world in order to evaluate the chloride penetration in concrete (Ann et al. 2009; Ye et al. 2012).

Fick's second law is often employed to describe chloride ion diffusion through concrete, despite the fact that cement matrix always, in fact, reacts with molecules including chloride ions (chloride binding or/and absorption by hydrations). This law is a model for the diffusion of a species that does not react into a medium that is only partially infinite. The environment has a significant impact on the qualities of the medium. In addition, the material of reinforced concrete that is discovered in marine environments can, in general, be thought of as being saturated. This is because marine environments include a lot of water. In point of fact, when concrete is cast on location, it is initially saturated and continues to be continuously subjected to high levels of relative humidity (Othmen et al. 2018). It is, therefore, obvious that, in the case of marine structures, a chloride displacement into concrete should be considered by a diffusion equation. This is something that was done in certain research in order to examine chloride profiles that were derived from reinforced concrete structures in unsaturated conditions (Real and Bogas 2018). Fick's second rule is simple to comprehend when viewed from the point of view of an engineer, and the orders of magnitude of diffusion coefficient (or chloride profile) that may be obtained with the assistance of this law are correct and acceptable.

It is possible to determine the chloride ion diffusion coefficient at any given depth by applying the second law of diffusion proposed by Fick [Eqs. (1) and (2)]. Using the equations will allow you to accomplish this goal (Ann et al. 2009).

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

In Eq. (1), C represents the concentration of chloride at a depth x, where x is the distance to the surface at time t, and D represents the diffusion coefficient. Because Crank's solution offers an analytical solution to differential Eq. (1), this is the scenario in which it is applicable.

$$c(x,t) = c_\mathrm{s}\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_\mathrm{c}}} \times t\right)\right] \tag{2}$$

In Eq. (2), where x is the distance to the concrete surface in meters, t is the time in seconds, D_C is the diffusion coefficient in square meters per second, C_s is the surface chloride concentration in percentage of the weight of concrete, $C(x, t)$ is the chloride concentration at a depth x in meters at a time t in seconds in percentage of the weight of concrete, and erf is the error function according to Eq. (3).

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp\left(-u^2\right)\mathrm{d}u \tag{3}$$

In Eq. (3), where erf(z) is the error function complement, it is evident that lowering the diffusion coefficient of chloride ions is one way to control the amount of chloride ions that are able to penetrate a given material. This is because Eq. (2) shows that this is one of the ways to control the amount of chloride ions that are able to penetrate a given material. According to the findings of a number of studies, the ratio of water to cement, as well as the use of concretes made with natural pozzolans blended cement, can have a significant impact on the mechanical resistance, early age shrinkage, cracking, water permeability, and carbonation depth of the concrete. Additionally, the use of natural pozzolans blended cement can have a significant impact on the carbonation depth of the concrete. The porosity of concrete can be reduced by lowering the amount of water used in comparison with the amount of cement. This decrease, in turn, can lead to an increase in the compressive strength of concrete while simultaneously leading to a decrease in the permeability of the concrete (Valipour et al. 2013; Medina et al. 2015).

According to Li research, the conditions of the working environment of the facing concrete can have a significant impact on the chloride ion penetration parameters. These conditions include the diffusion coefficient and even the surface chloride ion concentration. When the level of chloride that is present on the surface of the reinforcement reaches what is regarded as an essential concentration, corrosion of the reinforcement will start to occur (Li et al. 2015). On the basis of the existing environmental conditions, a variety of distinct functions have been incorporated for the critical chloride concentration. These functions have been accounted for below. The inquiry focuses on a certain region that is situated adjacent to the Persian Gulf, and one of the possible functions for this investigation is connected to that region. In this study, the onset time of corrosion has been proposed as the result of laboratory studies (based on the environmental conditions that are prevalent in the Persian Gulf), and experimental studies of the actual corrosive environmental conditions that are present in the southern regions of Iran have been carried out. These studies were carried out in order to confirm the findings of the previous laboratory studies.

3 Experimental Programs

3.1 Materials and Concrete Mixes

Within the scope of this research project's experimental programs, five distinct types of control concrete self-compacting concrete, designed cement composite, microsilica, and migration corrosion inhibitor were examined and analyzed. The many components of cementation were put to use. For the purposes of this investigation, concrete mixes with 10% cement replacement were made using locally produced type II Portland cement and microsilica sourced from the Azna ferrosilicon facility in Central Iran. In the case of the MCI sample, the inhibitor (MCI®-2020) was added to the mix water in accordance with the advised dosage rate of 6 kg/m^3 that was provided by the manufacturer. This was done in order to prevent the formation of MCI. The ECC mix was infused with the properties of the employed PVA fiber that had been used for, and the amount added was 4 kg/m^3. Both a high-range water reducer with a concentration of 0.0012% and a viscosity-modifying agent were incorporated into the SCC mixture simultaneously in order to achieve the desired level of workability.

Because concrete mixes are frequently developed for applications that require a high level of durability, three unique series of concrete mixes were developed with water-to-cementitious ratios of 0.38, 0.45, and 0.50, respectively. These ratios were chosen because concrete mixes are frequently produced for applications that call for a high level of durability. Every series has a total of six different mixes: control, microsilica, MCI, ECC, and SCC, in addition to a mix that has no additional admixture. It was decided that the total cement content of Type II marine concrete buildings should be approximately 400 kg/m^3, so each series was proportioned to have the same total cement content. This composition remained the same throughout the entirety of the series. It is possible to find it in Iran. The information regarding the ratios for the concrete mix is included in Table 1. The slump test was used to determine that the workability of all mixes could be maintained within the range of 125–25 mm by using the requisite quantities of a polycarboxylic ether-based superplasticizer. The riverbed in the vicinity may be mined for aggregates, or they may be found there naturally. These aggregates can be separated into two categories: coarse aggregates, which have a maximum size of 19 mm and a specific gravity of 2560 kg/m^3, and fine aggregates, which have a natural sand content and a specific gravity of 2500 kg/m^3 correspondingly. The coarse aggregates have a maximum size of 19 mm. The aggregates were successful in conforming to the requirements of ASTM C33. Concrete mixtures were prepared in the laboratory where the experiment was conducted.

3.2 Compressive Strength Test

Measurements were taken of the compressive strength of standard cubic concrete that had been allowed to cure for 7 and 28 days, respectively, so that the strength of the concrete mixes could be determined. The compressive strength test was carried out with the standard (BS 1881-116). In order to determine the amount of force that can be exerted by compression on concrete, cube-shaped specimens measuring 15 cm on each side were produced and tested. After that, these specimens were evaluated so that the compressive strength of each individual specimen could be determined. After being manufactured for 24 h, each specimen was removed from the mold and kept for a further 72 h in processing ponds that contained normal water heated to a temperature between 20 and 25 ℃. After this period of time, the specimens were ready for use (Fig. 1).

A test to measure the compressive strength of the samples at 7 and 28 days was performed while they were curing (Fig. 2).

The specimens were relocated to a study site in the city of Bandar-e-Imam Khomeini, which is located in Khuzestan

Table 1 Mixture proportions for concrete mixture studied

Mixes	w/c ratio	Water (kg/m^3)	Total cementitious (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	Superplasticizer % of total cementitious material	Micro silica (MS) (kg/m^3)	MCI (kg/m^3)	Fiber (kg/m^3)	VMA (%)
Control	0.38	152	400	760	1090	0.51	–	–	–	–
	0.45	180	400	760	1090	0.48	–	–	–	–
	0.50	200	400	760	1090	0.44	–	–	–	–
MS	0.38	152	360	760	1090	0.51	40	–	–	–
	0.45	180	360	760	1090	0.48	40	–	–	–
	0.50	200	360	760	1090	0.44	40	–	–	–
MCI	0.38	152	400	760	1090	0.51	–	6	–	–
	0.45	180	400	760	1090	0.48	–	6	–	–
	0.50	200	400	760	1090	0.44	–	6	–	–
ECC	0.38	152	400	760	1090	0.51	–	–	4	–
	0.45	180	400	760	1090	0.48	–	–	4	–
	0.50	200	400	760	1090	0.44	–	–	4	–
SCC	0.38	152	400	760	1090	0.51	–	–	–	0.0012
	0.45	180	400	760	1090	0.48	–	–	–	0.0012
	0.50	200	400	760	1090	0.44	–	–	–	0.0012

Fig. 1 Curing concrete specimens

Province on the southeastern shore of the Persian Gulf. This relocation took place when the time was deemed appropriate. At that location, they were put in the position where they were exposed to the tidal zone exposure condition (Fig. 3).

3.3 Powder Sampling and Chloride Ion Penetration Testing

The primary factor that leads to corrosion in the vast majority of offshore concrete structures is the introduction of chloride ions into buried reinforced concrete. This takes place due to the presence of salt water in the environment. As a consequence of this, it is of the utmost importance to do research on the resistance that concrete possesses against this form of penetration. In the course of this research, sampling was carried out at a variety of exposure times. Throughout the course of this investigation, several samplings were taken at a range of different exposure times. The concentration of acid-soluble chloride ions was measured over a period of 180 days spent in the tidal zone (during which time the sample went through repeated cycles of being wet and dry). In order to facilitate the process of drilling, an adjustable ruler was fastened to the drill. This made it possible to drill a sequence of holes, beginning at the location that was selected and moving through five stages based on the diameter of the drill. At each stage of the operation, a depth of 1 or 2 millimeters was worked (Fig. 4). In this inquiry, the approach that was followed was one that was deemed to be standard, and it was one that was obtained from ASTM C1152 (acid-soluble chlorine ions). The procedure consisted of three parts.

3.3.1 First Stage: Collection of Concrete Powder from the Structure

The powdering of the repaired concrete piles at this wharf was done in order to quantify, with an accuracy of 0.5 mm, the number of chloride ions that were present in the depth

Fig. 2 Compressive strength test machine

of the concrete. This was accomplished by measuring the number of chloride ions that were present in the powdered concrete. The first millimeter's worth of powder was thrown away as the norm dictated that it should not be used. In order to create a chloride ion profile, it was necessary to collect at least 10 g of powdered concrete from a range of depths. This was done so that the profile could be drawn. In order to accomplish this goal, the concrete powder that was obtained from it was first perforated, and then, it was stored inside of a plastic zip in order to prevent any moisture from entering. This was done to ensure that the powder would not get contaminated. In the end, the specimens were brought to the experimental area, and before continuing on to the stage of solution preparation, the specimens were prepared by passing the powders through a sieve with a 70-point opening. This was done before going on to the next stage of the process, which involved the manufacture of the solution.

3.3.2 Second Stage: Solution of Chloride Ion in Nitric Acid

In accordance with the requirements of the ASTM C114 standard, a solution was developed. After passing 10 g of concrete powder through a screen set at a degree angle, the powder was transferred to an Erlenmeyer, and then, 75 ml of distilled water were added to the flask. The flask was allowed to sit for 10 min before being used. After that, 25 ml of distilled water were added gradually in order to dilute the nitric acid. This process took place almost soon after the initial step. After that, the dilution was put into the concrete mixture, and then, it was gently agitated for somewhere in the range of 2–3 minutes. At this point in the process, the acid was applied to the concrete powder in order to dissolve any and all chloride ions that may have been present. To ensure that the chloride ions were completely dissolved in the acid, the solution was spiked with two to three drops of the methyl

Fig. 3 Concrete specimens subjected to tidal zone exposure condition in the Persian Gulf

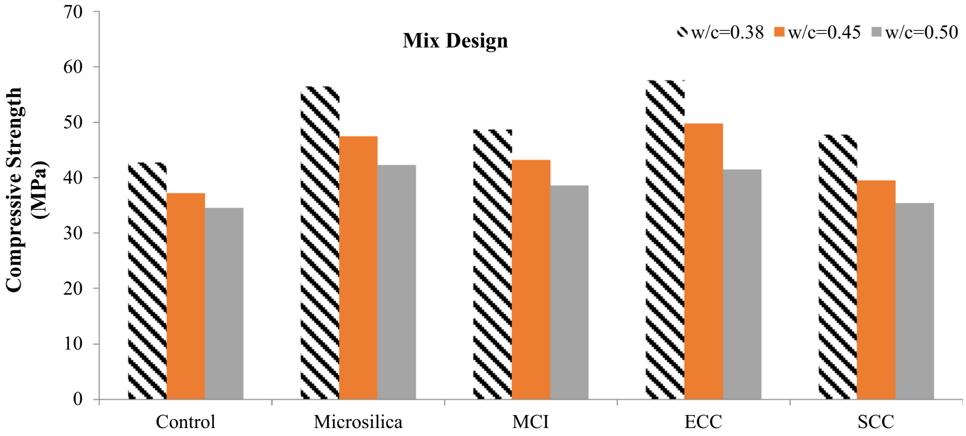

Fig. 4 Results of compressive strength testing age of concrete at 7 days for w/c = 0.38, 0.45, and 0.50

orange index acid. This was done in order to achieve the desired result. After this, it was discovered that the chloride ions had been fully dissolved in the acid. After the solution had been heated to a high temperature and brought to a boil, it was strained through filter paper after it had reached the boiling point. The solution was regarded to be finished once the initial solution had been diluted with distilled water to a volume of 250 ml in order to reach the desired concentration. Each of the steps has an accompanying illustration, which is found in Fig. 4.

3.3.3 Step 3: Third Stage: Determination of Chloride Ions Concentration in the Solution

It was necessary to take some measurements of the solution in order to determine how much of it had been poured into the machine. It was necessary to obtain the value expressed in terms of grams divided by ten in order to calculate the number of ions in solution in order to precisely measure the amount of chloride ions that were present in the concrete. This was accomplished by dividing the value obtained in the previous step by ten. The tetrapetometric equipment that was installed at the Imam Khomeini Port Investigation Center for Concrete Technology and Durability was utilized in the course of this investigation. The technique that required to be followed was to first determine the amount of solution that needed to be poured into the apparatus, then measure out that exact amount of solution. First, the total number of chloride ions in the solution must be calculated in grams before proceeding to the next step, which is the calculation of the percentage of chloride ions that are present in the concrete. The next step was to take this result and divide it by 10 g in order to calculate the percentage of chloride ions that were found in the concrete. Last but not least, it was necessary to determine how many chloride ions are contained in the concrete. In this experiment, the quantity of chloride ions in solution was measured by passing the solution through the apparatus three times, with each passage using a different volume. The results were the weighted average of the solution's readings.

4 Results and Discussion

4.1 Compressive Strength

In an effort to increase the accuracy of our test results, we conducted research on three separate samples with water-to-cement ratios of 0.38, 0.45, and 0.50 respectively. The findings of the compressive strength test after 7 days and after 28 days are displayed in Table 2 and Figs. 5, 6, and 7, respectively. The compressive strength of concretes containing microsilica is higher than the compressive strength of ordinary concretes of any age, and the difference between the two gets more evident as the water–cement ratio falls. The compressive strength of the concrete specimens that had been aged for 28 days was much greater than that of the concrete specimens that had been aged for 7 days, as shown in Figs. 5 and 6. This was the case with each of the five different concrete samples that were examined.

When compared to the sample that acted as the control, the increase in resistance of MS, ECC, MCI, and SCC to cement 0.38 after 28 days with water was approximately 21%, 19%, 6%, and 4%, respectively, as shown in Figs. 5 and 6. The sample that acted as the control was used as a comparison. These findings shed light on the significant role that pozzolanic components play in the manufacturing process of concrete. It is probable that this is due to the pozzolanic effect that concrete has on the environment. It is necessary for there to be calcium hydroxide present in the pozzolanic materials for the pozzolanic reaction to be able to take place. As a consequence of this, there is an abundance of calcium silica hydrate (C–S–H).

Table 2 Compressive strength of concrete specimens

Mixes	w/c	Compressive strength (MPa(	
		7 days	28 days
Control	0.38	42.7	55.2
	0.45	37.2	50.5
	0.50	34.5	48.7
MS	0.38	56.4	69.6
	0.45	47.5	66.2
	0.50	42.3	58.7
MCI	0.38	48.7	58.8
	0.45	43.2	53.3
	0.50	38.6	50.9
ECC	0.38	57.5	68.1
	0.45	49.8	65.4
	0.50	41.5	56.4
SCC	0.38	47.8	57.7
	0.45	39.5	54.8
	0.50	35.4	49.1

4.2 Corrosion Rate Potential Measurement

In order to evaluate the steel's tendency to corrode, the samples were put through a curing process that lasted for 28 days in the water pond and then were subjected to the conditions of the maritime environment for a period of 16 months (Fig. 7).

In accordance with the ASTM standard C-876-15 for copper/copper sulfate electrode (Cu/CuSO4), this test was carried out with a device known as a half-cell. You may find the criteria or limits of the potential (Ecorr) values related with the likelihood of corrosion for implanted rebar specimens in Table 3 of this standard. These can be discovered in the standard because it outlines the criteria or limits (ASTM 2015).

After a period of 28 days spent curing in normal water, the concrete samples were removed from the ponds and taken to the Technology and Durability Research Centre of Amir Kabir University, which is situated in Bandar-e-Imam Khomeini. Tests for corrosion were conducted there for a period of 16 months in the tidal zone (which experiences cycles of wetting and drying) in the environment of the Persian Gulf. The specimens underwent these evaluations once every 30 days, and the results of the numerous studies were compared to one another after each round of testing. The results of the experiment are summarized in Table 4, which contains the readings that were taken

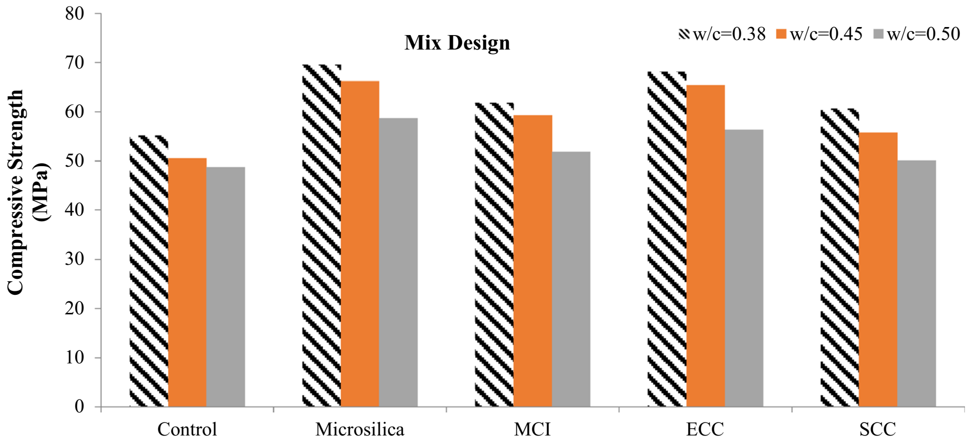

Fig. 5 Results of compressive strength testing age of concrete at 28 days for w/c = 0.38, 0.45, and 0.50

Fig. 6 Preparations for the corrosion tests conducted on preparations for the corrosion tests conducted on research site in the city of Bandar-e-Imam Khomeini

to determine the half-cell potential. When the evaluation criteria in Table 3 are used, it is evident that the potential Ecorr is low (350 mV) in the control, ECC, and SCC concrete specimens, which suggests that there is a 90% possibility of corrosion. This is the case regardless of whatever concrete specimen is being considered. It makes no difference whether the specimens are ECC, SCC, or control; this is always the case. When comparing the effect of using MCI and microsilica materials in concrete, the data that are given in Figs. 8, 9, and 10 reveal that there are some fascinating differences between the two types of materials. At this point in time, samples that have had microsilica and alkanolamine-based inhibitors placed to the surface of the concrete from the beginning have nobler potentials.

It is clear from looking at Figs. 8, 9, and 10 that the rate of corrosion goes through a cycle of first increasing and then decreasing. The rust layer is very thin at the first stages of corrosion, and the corrosive ions in the medium directly stick to the surface of the substrate and disperse. As a result, the rate of corrosion displays a rapid upward trend at the beginning stages of corrosion. In addition, steel that has been buried in concrete is generally inert since it is subjected to an alkaline environment with a pH > 12. When the passive layer is damaged, rust spots made of steel will appear on the surface of the concrete. In the event of a chloride or carbonate assault, chemical processes that lead to corrosion can take place. When steel corrodes in concrete, it dissolves in the pore water, which results in the release of electrons. The pH of concrete that is not subjected to an external environment that is corrosive will normally fall somewhere in the range of 12.5–13.5. In addition to this, there is no rusting. The dependency of corrosion potential and corrosion rate on a wide variety of parameters, such as temperature and relative humidity, can lead to some change in the results over the course of time. The electrical resistance of concrete lowers as temperature and relative humidity continue to rise, which ultimately results in an increase in the possibility of corrosion as well as its rate. Because these tests were conducted at different periods of the year, we were able to notice a rise in potential in a positive direction due to the reduction in heat during the winter season. This was the case because these tests were carried out at different times of the year.

Table 3 Probability of corrosion according to half-cell potential values as per ASTM C-876-(ASTM 2015)

(Ecorr) (mV)	Corrosion condition
(Ecorr) > − 200	Low (10% of risk corrosion)
− 200 > (Ecorr) > − 350	Intermediate corrosion risk
− 350 > (Ecorr) > − 500	High (< 90% of risk corrosion)
(Ecorr) < − 500	Severe corrosion

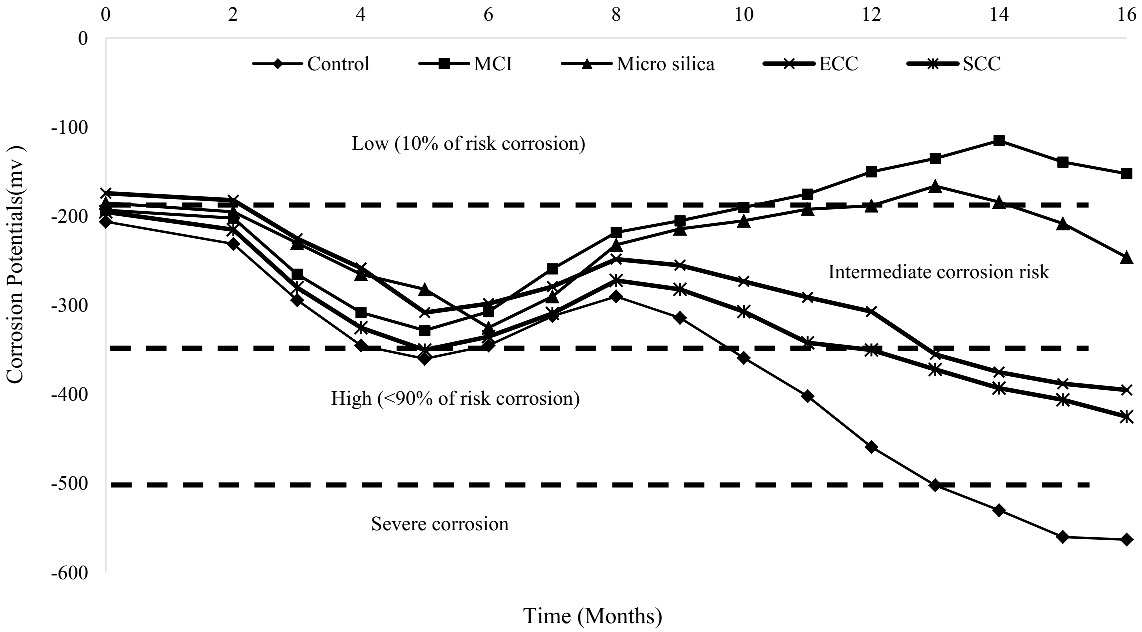

Fig. 7 Corrosion potentials for mixtures with w/c = 0.38

Table 4 Results of corrosion potential measurements different times

Months	w/c														
	Control			MCI			Microsilica			ECC			SCC		
	0.38	0.45	0.50	0.38	0.45	0.50	0.38	0.45	0.50	0.38	0.45	0.50	0.38	0.45	0.50
1	−206	−236	−255	−193	−215	−240	−185	−198	−219	−184	−180	−202	−195	−225	−248
2	−231	−265	−305	−202	−235	−275	−195	−220	−235	−182	−205	−225	−215	−252	−287
3	−294	−310	−338	−265	−280	−300	−230	−242	−278	−225	−235	−268	−280	−301	−325
4	−345	−373	−395	−308	−312	−335	−265	−305	−345	−258	−270	−325	−325	−368	−375
5	−360	−395	−420	−328	−355	−385	−282	−345	−372	−308	−354	−393	−350	−385	−402
6	−345	−362	−390	−307	−325	−350	−325	−315	−335	−298	−325	−356	−335	−355	−370
7	−312	−324	−355	−259	−288	−305	−290	−309	−315	−279	−280	−302	−309	−320	−335
8	−290	−300	−360	−218	−245	−278	−232	−275	−305	−248	−265	−275	−272	−280	−312
9	−314	−359	−385	−205	−222	−271	−214	−235	−262	−255	−270	−302	−282	−295	−335
10	−359	−372	−402	−195	−211	−255	−205	−215	−245	−273	−295	−315	−307	−325	−354
11	−402	−427	−440	−175	−185	−215	−192	−210	−225	−291	−305	−340	−342	−373	−395
12	−459	−473	−495	−150	−163	−180	−188	−205	−215	−307	−345	−372	−350	−380	−410
13	−502	−522	−535	−135	−148	−175	−166	−175	−195	−355	−380	−395	−372	−395	−445
14	−530	−551	−570	−115	−125	−140	−184	−195	−215	−375	−400	−408	−393	−408	−470
15	−560	−585	−605	−139	−158	−173	−208	−217	−255	−388	−411	−415	−406	−430	−478
16	−563	−605	−630	−152	−175	−190	−246	−275	−292	−395	−422	−440	−425	−445	−495

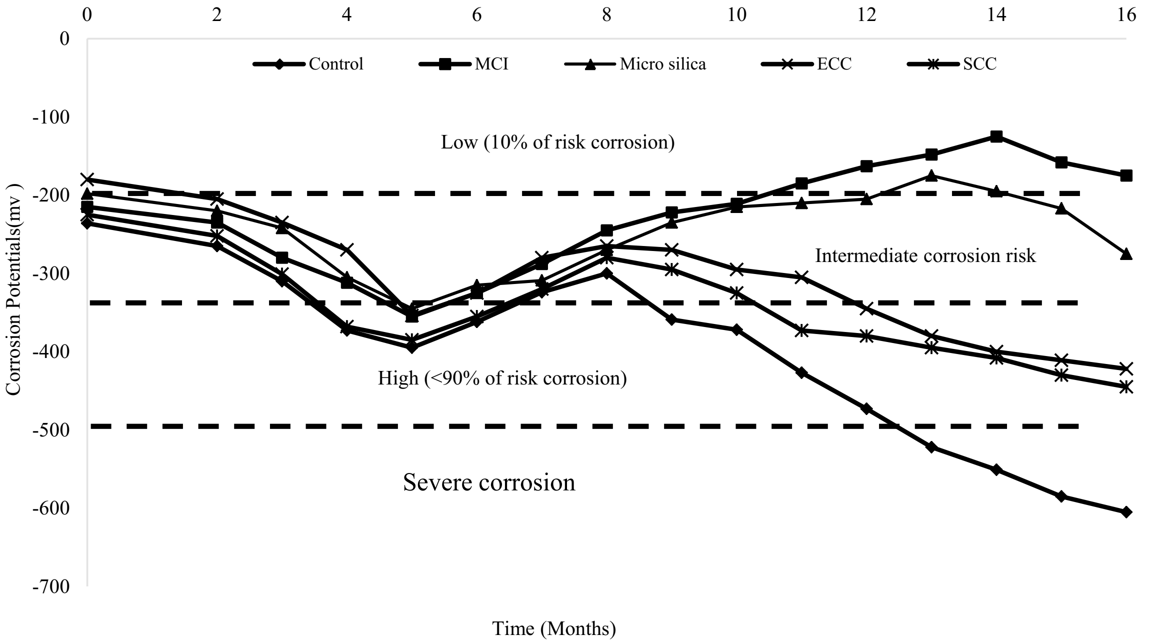

Fig. 8 Corrosion potentials for mixtures with w/c = 0.45

4.3 The Chloride Ion Penetration Test

After the profiles had been subjected to the tides for a period of 180 days, we were able to determine the amount of acid-soluble chloride ions that were present in them. Table 5 demonstrates how the concentration of chloride ions can be utilized to determine the risk of rusting in reinforcement (Real and Bogas 2018). This criterion was conceived of and formulated by the National Institute of Standards and Technology. These guidelines have been applied in

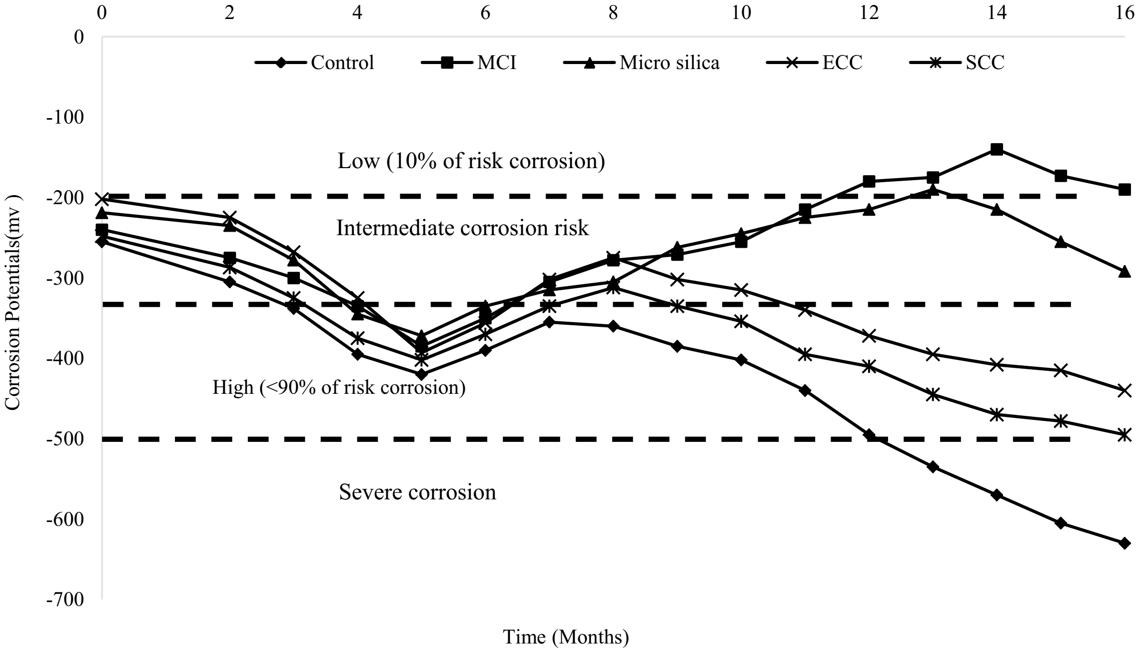

Fig. 9 Corrosion potentials for mixtures with w/c = 0.50

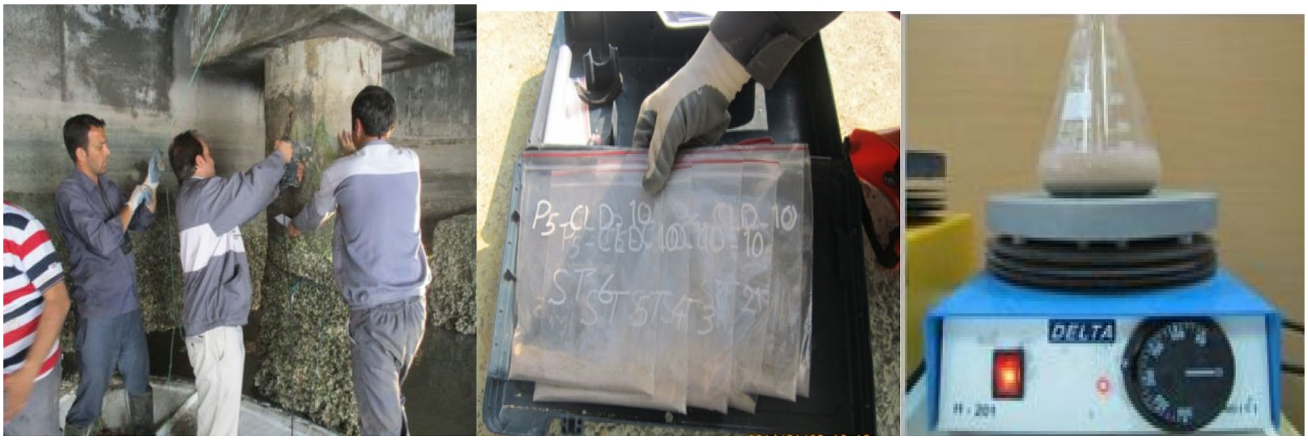

Fig. 10 Drilling of concrete piles and collecting powder from the restored concrete at wharf No. 5 in Imam Khomeini Port, Iran

this inquiry since the findings of the chloride ion concentration in accordance with the standard technique ASTM C1152 are reliant on the weight percentage of concrete. As a direct result of this, a limit of greater than 14% by weight of concrete is regarded a criterion for a high corrosion risk, whereas a limit of 0.07 by weight of concrete is considered a criterion for a moderate corrosion risk. Both of these limits are measured in percentages relative to the weight of the concrete. In addition, a weight of 0.05 concrete satisfies the requirements for a low corrosion risk, which is defined as a risk that is lower than 0.03 of its kind. This ensures that the concrete will not corrode quickly.

Following the completion of repairs at Imam Khomeini Port's concrete wharf 5, the structure was chlorinated to prevent chlorine ions from entering the structure. The findings of the investigation into the level of chloride ion concentration are presented in Table 5, and the table also contains the findings of the investigation into the level of chlorine ion penetration (Figs. 11, 12, and 13).

4.4 Chloride Concentrations in Concrete

In order to calculate the rate of corrosion, one of the most significant parameters that all of the presented models require is the amount of chloride that is located in close proximity to the reinforcement. Conducting chloride concentration profiles is the method that is most frequently used to obtain this information. When chlorides come into contact with concrete, the concrete itself needs to have a low permeability in order to prevent the chlorides from passing through the material. This is done in an effort to stop the assault from happening. Having a low water-to-cement ratio means that the concrete will have a better permeability, despite the fact that it makes the concrete less workable on the construction site. We are in a position to make the following assertion in light of the data that were shown earlier: The water-to-cement ratio of the concrete is directly influenced by the porosity of the concrete. This is because concrete with a low porosity will often have a low permeability level. The reason for this is because of the relationship between the two. The chloride concentrations that were examined were expressed as a percentage of the total mass of the concrete (%) for a variety of exposure times, and concrete specimens with varied water-to-cement ratios were exhibited. In addition, the chloride concentrations that were analyzed were displayed. Table 6 presents a summary of the chloride concentrations that were computed using the potentiometric titration method at the various levels of the reservoir. These concentrations were determined at each level of the reservoir. A graphical illustration of the outcomes after 180 days is found in Figs. 11, 12, and 13. An evaluation was performed on each of the mixtures to establish how resistant they were to the penetrating effects of chloride ions. In this study, the recommended ranking of chloride ion penetrability by ASTM C1202 (Table 5) and the actual results were compared and contrasted with one another. The utilization of MS and MCI, as demonstrated by the data, considerably increased the chloride ion penetration resistance of mix control concrete, as well as ECC and SCC. The outcomes of this comparison can be considered in light of mix-controlled concrete. As the proportion of water to cement in concrete increases, so does the amount of chloride that is contained inside it. Generally, the results are graphically presented in Figs. 11, 12, and 13. There is a direct correlation between the water-to-cement ratio and the quantity of chloride ion penetration; however, as the depth of the concrete grows, the amount of chloride ion penetration significantly decreases.

Table 5 Corrosion risk at given chloride contents (Broomfield 2011)

% Chloride by mass of cement	% Chloride by mass risk of cement of sample (concrete)	Risk
< 0.2	< 0.03	Negligible
0.2–0.4	0.03–0.06	Low
0.4–1.0	0.06–0.14	Moderate
> 1.0	> 0.14	High

5 Conclusions

During the course of this piece of study, chloride-induced corrosion was investigated as a potential explanation for why offshore reinforced concrete structures fail at a higher rate than structures made of other materials. The P28 wharf

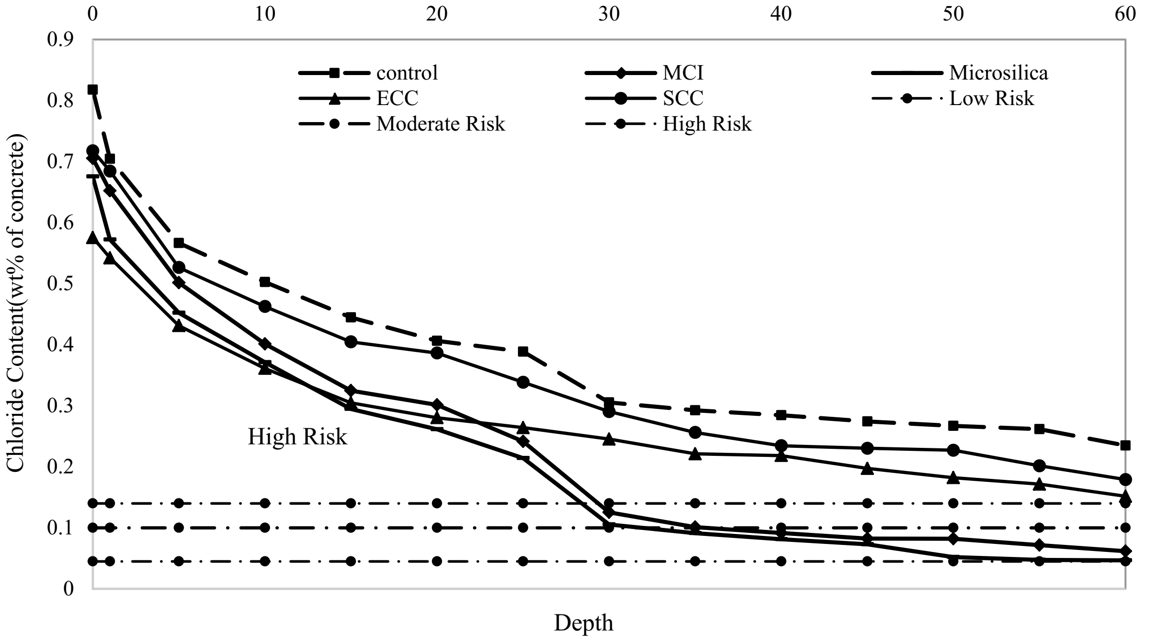

Fig. 11 Chloride profile concentration in mortar at different depths exposure in the tidal zone: w/c = 0.38

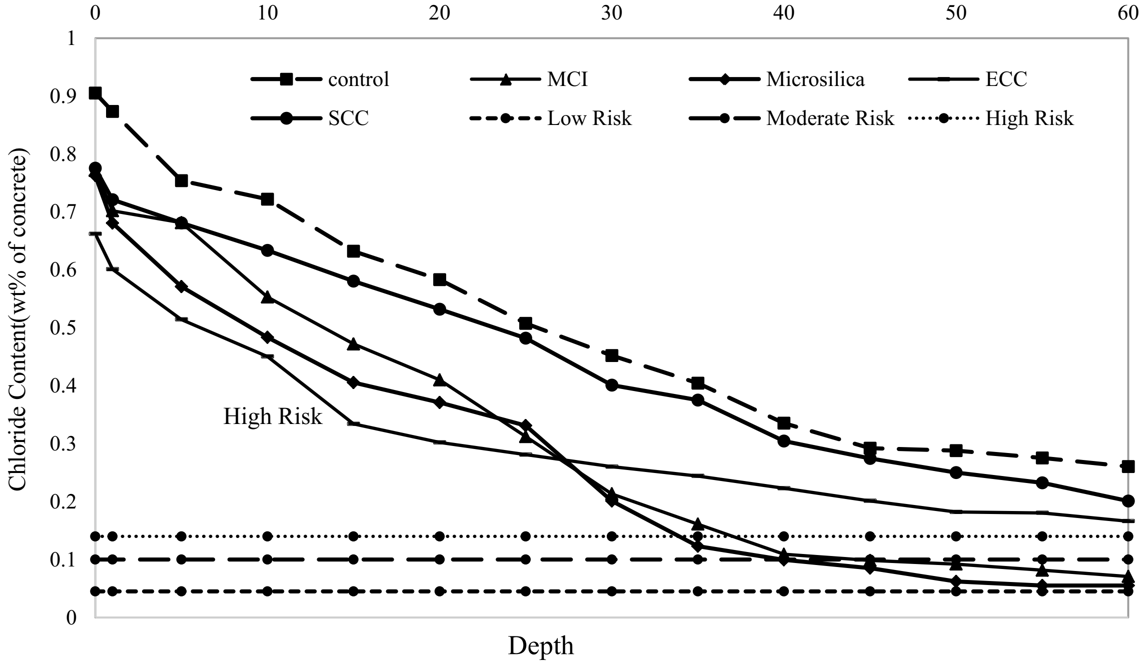

Fig. 12 Chloride profile concentration in mortar at different depths exposure in the tidal zone: w/c = 0.45

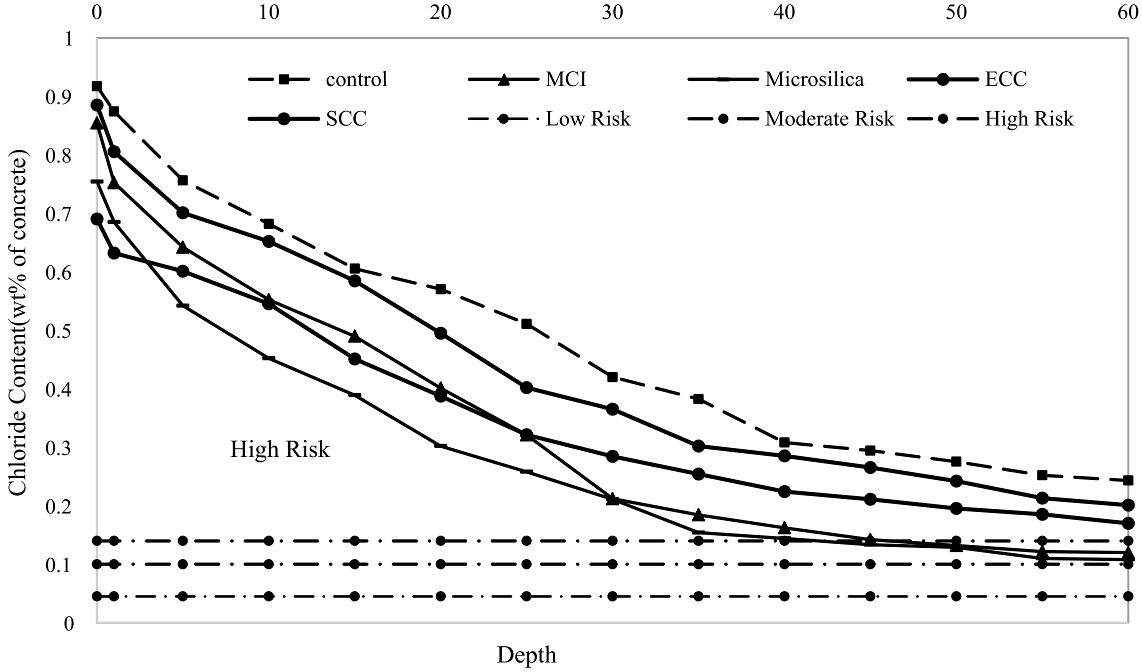

Fig. 13 Chloride profile concentration in mortar at different depths exposure in the tidal zone: w/c = 0.50

at Imam Khomeini Port, which is one of the most essential and vital ones in the country due to its location on the Persian Gulf, was also researched on five different types of concrete. This was done in order to better understand how each of these types of concrete performs. This was done so that we could identify which of the two would be the most successful.

- The compressive strength test on cubic specimens, which lasted for a total of 7 and 28 days, respectively, demonstrates that the concrete containing microsilica has the

Table 6 Results of chlorine ion diffusion profile in wharf 5 Port at Imam Khomeini—Iran

Consumable concrete	Control	Microsilica	MCI	SCC	ECC
Chlorine level in concrete	High	Low	Low	High	High

highest compressive strength, whereas control concrete and SCC concrete have the lowest compressive strength. The test was conducted on cubic specimens.

- The specimens were put through a prospective (Ecorr) corrosion test, and the results revealed that, after 16 months, MCI concrete had the lowest level of corrosion, but control concrete and SCC concrete had the highest degree of corrosion. The experiment was conducted using MCI concrete, control concrete, and SCC concrete.
- At the port of Imam Khomeini, a chloride ion penetration and powdering test was conducted from five separate locations on wharf 28, which had been severely corroded and patched up with concrete. The structure had been destroyed by significant corrosion. The procedure was carried out when the infant was 180 days old. It was discovered that the amount of chloride ion penetration at the surface and at the depth of MCI and microsilica concrete to the end of the powdered area (55 mm) shows a low corrosion risk; on the other hand, the amount of chloride ion penetration in SCC concrete shows a high corrosion risk, which indicates the permeability of SCC concrete. Both of these findings point to the fact that MCI and microsilica concrete have a lower corrosion risk than SCC concrete. The amount of chloride ion penetration at the surface as well as at the depth of both types of concrete was used to come to this conclusion.

Research showed that the southern coast of Iran is a good location for using organic corrosion inhibitors based on polycarboxylate amino alcohol, and MCI® 2020 worked extremely well to cut down on the amount of corrosion that occurred. According to the findings of the research, organic corrosion inhibitors are a good site to use. As a consequence of this, one might reach the conclusion that the utilization of organic corrosion inhibitors is the most efficient method for preventing the corrosion of rebar. This is because of the results that were obtained.

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