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Review

A Review of Durability Issues of Reinforced Concrete Structures due to Coastal Soda Residue Soil in China

Linjian Wu, Zhouyu Xiang *, Han Jiang, Mingwei Liu *, Xueli Ju and Wenxiao Zhang

National Engineering Research Center for Inland Waterway Regulation, School of River and Ocean Engineering, Chongqing Jiaotong University, 66 Xuefu Road, Nan'an District, Chongqing 400074, China
* Correspondence: xzy@mails.cqjtu.edu.cn (Z.X.); mingwei_liu@126.com (M.L.)

Abstract: Soda residue soil (SRS) is a man-made engineering foundation soil formed by soda residue; it is mainly distributed in coastal areas in China. SRS is rich in a variety of corrosive salts, among which the concentrations of chloride ions are about 2–3 times that of seawater. These highly concentrated chloride ions migrate and diffuse in reinforced concrete (RC) structures built on coastal SRS through multiple transport mechanisms. However, current research on the durability of RC structures exposed to the coastal SRS environment has not led to the publication of any reports in the literature. SRS may be classified by analyzing the quantitative relationships among the corrosive ions it contains. In this paper, the deterioration of RC structures due to the corrosive saline-soil environment in China is discussed, and advances in RC structure durability under such circumstances are reviewed. Our findings show that a corrosive environment, especially when this is a result of coastal SRS, has a significant influence on the deterioration of RC structures, greatly threatening such buildings. A series of effective measures for enhancing the durability of RC structures in saline soil, including improvements in concrete strength, reductions in the water–binder ratio, the addition of mineral admixtures and fiber-reinforcing agents, etc., could provide a vital foundation for enhancing the durability of RC structures which are at risk due to coastal SRS. Vital issues that must be investigated regarding the durability of RC structures are proposed, including the transport mechanism and a prediction model of corrosive ions, dominated by chloride ions (Cl^-), in SRS and RC structures, the deterioration mechanism of RC materials, a long-term performance deduction process of RC components, durability design theory, and effective performance enhancement measures. The findings of this paper provide some clear exploration directions for the development of basic theories regarding RC structure durability in coastal SRS environments and go some way to making up for the research gap regarding RC structure durability under corrosive soil environments.

Keywords: coastal reinforced concrete; soda residue soil; chloride transport; durability issues

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1. Introduction

Reinforced concrete (RC) is a composite material composed of rebar and concrete. It takes advantage of the positive characteristics of both of its components and is widely used in roads, bridges, ports and offshore infrastructure [1–5]. As noted in previous studies, a large number of RC structures do not reach their predetermined design service life, but rather, fail due to insufficient durability [6–15]. The service environment of RC structures is one of the most immediate and significant factors affecting their structural durability, especially regarding long-term exposure to ocean salt environments [16–25]. The corrosion of steel caused by the intrusion of chloride ions into concrete results in concrete expansion and cracking, which are the main reasons for durability failures of RC structures [26–35].

Sodium carbonate (soda ash, Na_2CO_3) is a basic organic chemical raw material which is widely used in the food, textile, medicine and metallurgical industries, among others. [36–39]. Soda residue is an industrial waste residue generated by the production of soda ash based on the ammonia–soda method [39–41] (see Figure 1); its makes up about 30% of the total soda ash volume [42]. Due to the absence of chemical components in soda residue, such as soluble heavy metals that could pollute the aquatic environment, soda residues are often disposed of by direct dumping into the ocean or by being stacked in the open air in coastal areas [43]; this is why most ammonia–soda factories are built in coastal areas. Over the years, the amount of soda residue produced by ammonia–soda factories in coastal areas in China has increased dramatically. The accumulated soda residue from the Weifang Haihua ammonia-soda factory in Shandong Province has reached 20 million tons, that from the Tangshan Sanyou factory in Hebei Province has exceeded 10 million tons [44], and over the past 80 years, that produced via the ammonia–alkali process by the Tianjin Soda Plant has exceeded 15 million tons [45]. As such, over the years, a large volume of soda residue has accumulated in the land area of the north harbor basin in Tianjin Port, forming a "soda residue mountain", which covers an area of about 3.5 million m^2, as shown in Figure 2. The long-term accumulation of such a large amount of soda residue will place a burden on a number of coastal land resources [46]. In addition, the soda residues drying in the open air readily form a dust which pollutes the air due to wind. Moreover, when soda residue become soaked in water, it readily forms highly concentrated solutions of chloride ions which can penetrate into the groundwater, increasing the abundance of corrosive soluble salts in the soil environment, resulting in soil salinization and adversely affecting the surrounding ecological environment [43,47,48].

In order to solve the aforementioned problems, Tianjin Port carried out a relocation and treatment program for the "soda residue mountain" located in the north harbor basin. The soda residue was, for the most part, placed into a newly excavated "storage residue pit" after manual physical transportation. As a result, a soda residue soil (SRS) foundation covering a total area of almost 800,000 m^2 was formed, as shown in Figure 2d. According to existing research, the soda residues have the characteristics of a low strength, high compressibility and high sensitivity, and external effects are having significant impacts on the strength, deformation and bearing characteristics of the soil [49–51]. Therefore, soda residues should be strengthened before they are used as engineering foundation soils. It was planned to construct coastal RC infrastructure on such strengthened soils, such as port yards, coastal roads and buildings. On the basis of random sampling of the SRS in the storage residue pit in Tianjin Port, the pH value and moisture content of the undisturbed SRS were measured at about 9.5 and 155%, respectively. Moreover, the soluble chloride ion (Cl^-) content was about 8.36 × 10^4 mg/kg (8.36%), mainly comprising $CaCl_2$ and NaCl, and the contents of soluble SO_4^{2-} and Mg^{2+} were almost 1.88 × 10^3 mg/kg and 8.61 mg/kg, respectively.

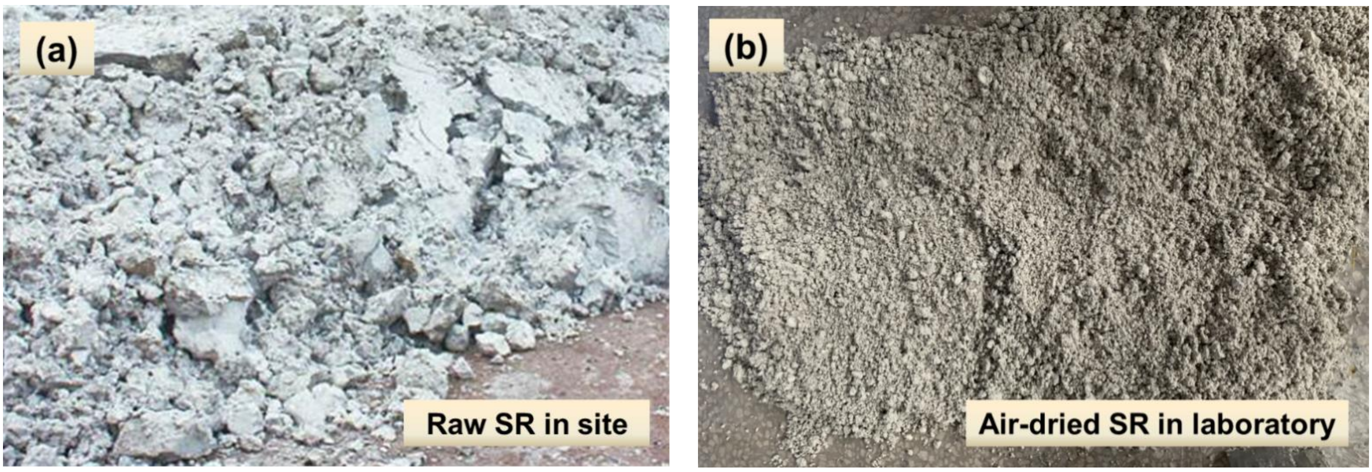


Figure 1. Soda residue (SR): (**a**) raw SR; (**b**) air-dried SR.

Figure 2. Stacking fields of soda residues in China [44]: (**a**) Weifang City in Shandong Province; (**b**) Tangshan City in Hebei Province; **(c)** Lianyungang City in Jiangsu Province; (**d**) Tianjin Port in Tianjin City.

In summary, the chloride ion (Cl^-) content in soda residues with a high moisture content was about 2–3 times that of seawater (the Cl^- concentration in seawater is about 3.5%). High concentrations of Cl^- in the pore solution of SRS with a high moisture content can intrude into concrete through multiple transport mechanisms and induce the corrosion of rebars and the deterioration of RC material properties, seriously threatening the durability of RC structures constructed on coastal SRS.

SRSs have the characteristics of low strength, high compressibility and high sensitivity. The bearing capacity of coastal SRS foundations and the durability of RC structures built on them are the two important issues that urgently need to be addressed for the application of soda residue in coastal engineering. At present, most of the previous investigations related to SRS have focused on its mechanical properties, such as its strength, deformation characteristics, foundation-bearing capacity, etc., but there is no public literature report on the durability issues facing RC structures caused by the influence of chloride ions in coastal SRS corrosion environments.

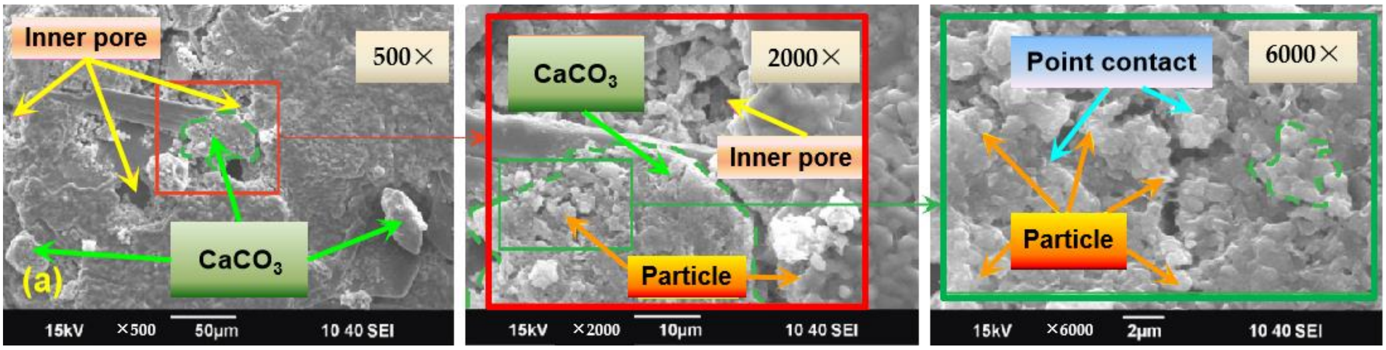
The performance of SRS foundations is characterized by their large area, volume, and range, their high moisture and chloride ions contents, as well as their deep thickness foundation. The effect of an SRS environment on the durability of coastal RC structures cannot be neglected. The question of how to scientifically evaluate, reasonably design and accurately predict the long-term performance, bearing capacity and service life of RC structures exposed to a complex coastal SRS environment with the aforementioned characteristics are significant issues and need to be addressed urgently.

Therefore, this paper focuses on significant issues concerning the durability of RC structures in such a setting. The SRS soil type is classified by analyzing the quantitative relationship between soda residue, which is used as engineering foundation soil, and its corrosive ions. On this basis, using a research methodology obtained through a literature review, the deterioration of RC structures in corrosive soil environments in China is elaborated, and advances in RC structure durability are reviewed. Some measures to enhance the durability of RC structures are summarized, and the influences of the corrosive soil environment on the durability of the RC structure are expounded. There has been no published literature report on the influence that chloride ions have on the durability of RC structures in coastal SRS environments to date. The results of the present study will help to promote the development of research on a basic theory regarding RC structure durability, which could have some important scientific value and make up for the research gap in this field.

2. Material Properties of SRS

2.1. Using Soda Residue as Engineering Foundation Soil

According to existing research, using raw soda residues (see in Figure 1) as an engineering foundation soil is the most primary, effective and economic measure for the comprehensive treatment of soda residue [39,52]. The mineral composition, chemical composition, microstructure and physical–mechanical properties of SRS formed by soda residue differ from those of general real engineering soils. The microcharacteristics of SR, obtained using the XRD and SEM approaches, are exhibited in Figure 3 [44,52–55]. Based on our analyses of the mineral phases, morphologies and chemical components, the obtained soda residue samples mainly comprised halite, gypsum and calcite crystal phases, and the microstructure was loose and porous. A single particle of calcium carbonate ($CaCO_3$) has a size of 2~5 um. $CaCO_3$ particles agglomerate with each other by point contact, although the cementation of agglomerate particles is very weak. The surface of the $CaCO_3$ aggregate structure is very rough, and lots of pores with different sizes are visible on the surface and inside the aggregate particles. These pores are connected with each other, which results in a very high moisture content and the presence of more corrosive ions in SRSs compared with other engineering foundation soils.



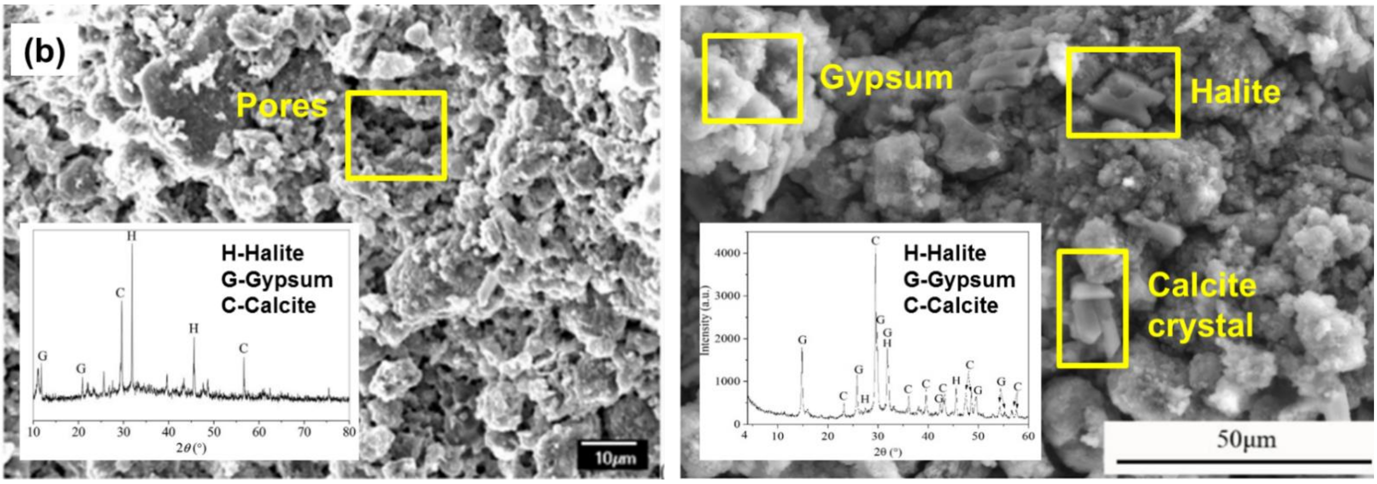


Figure 3. SEM and XRD results of soda residue: (**a**) Microstructure of soda residue at various magnifications [52]; (**b**) XRD patterns and SEM photos of soda residue [44,53,54].

2.2. Corrosive Property of SRS for RC Structure

The raw SRS in the storage residue pit at Tianjin Port, China, is taken as an example. The basic physical properties and the contents of soluble corrosive ions in the residue samples were determined by a random field sampling test conducted by our research team, as shown in Table 1.

Table 1. Basic physical properties and corrosive ion content of SRS samples.

Measurements	Moisture Content (%)	pH Value	Cl^- (%, mg/kg)	SO_4^{2-} (%, mg/kg)	Mg^{2+} (%, mg/kg)
Maximum value	160	11.28	88233.08	2012.16	10.06
Minimum value	149	7.720	79178.37	1730.45	7.240
Average value	155	9.500	83565.37	1883.39	8.610

The measurements listed in Table 1 show that the water-soluble Cl^- content in raw SRS was the highest, i.e., almost 2–3 times than that of seawater. The second was water-soluble SO_4^{2-}, whose concentration was one order of magnitude lower than that of Cl^-. In addition, the SRS also contained a small amount of water-soluble Mg^{2+}. According to the literature, the tested Cl^- content was consistent with that of the Qarhan saline soil area in Qinghai Province, China [56,57], although the Cl^- content of soda residue from Tianjin Port was much higher than that in the coastal saline soil of Tianjin [58]. Under the conditions of long-term groundwater immersion in SRS, the rebars of RC structures are mainly corroded by Cl^- [59].

2.3. Soil Type of SRS

The physicochemical properties of the soil, including the type and quantity of corrosive medium therein, pH, texture, etc. affect the corrosion of RC structures. The larger the soil porosity and the higher the water content, the stronger the ability of the soil pore liquid phase to dissolve various corrosive salt ions and the higher the corrosion in embedded concrete and RC structures [60]. Saline soil is widely distributed in China (Figure 4), with a total area of about 3.64 × 10^7 hm^2, accounting for 4.88% of the available land in the nation; it is mainly distributed in coastal and northwest areas [61]. According to the corrosion observed in RC structures, saline soil can be classified into two types: inland and coastal [60]. Inland saline soil can be further classified into eastern semi-arid-semi-humid, central arid, western strong arid, and arid basin saline soil [62]; these types are mainly distributed in Xinjiang, Qinghai, Gansu, Inner Mongolia and other regions of China.

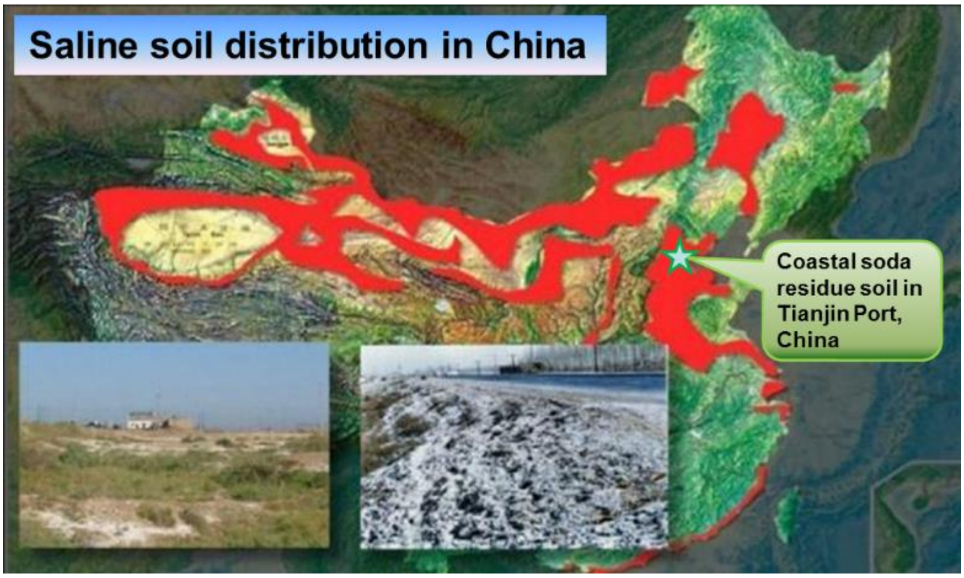


Figure 4. Distribution of saline soil in China [61].

The measured pH value of saline soil from Golmud Yanqiao Avenue, Qinghai Province, China, was about 8.0–9.5, and the contents of Cl^- and SO_4^{2-} were about 0.82% and 1.43%. Coastal saline soil is mainly distributed in coastal areas of China, with pH values of about 7.5~8.5, Cl^- contents of about 2.62%, and SO_4^{2-} contents of about 0.28%. According to the salinity properties of the soil, i.e., the ratio of Cl^- to SO_4^{2-}, $m_{C\text{-}S}$, as exhibited in Equation (1), saline soils may be divided into four categories, i.e., chlorine, chlorite, sulfite and sulfate [63], as shown in Table 2.

$$m_{C\text{-}S} = \frac{m\left(Cl^-\right)}{m\left(SO_4^{2-}\right)} \tag{1}$$

where $m(Cl^-)$ is the chloride ion content (%) and $m(SO_4^{2-})$ is sulfate ion content (%).

Table 2. Initial classifications of saline soils used in engineering [63].

Type of Saline Soil	Chlorine Saline Soil	Chlorite Saline Soil	Sulfite Saline Soil	Sulfate Saline Soil
$m_{C\text{-}S}$	>2.0	1.0~2.0	0.3~1.0	<0.3

In addition, according to the degree of soil salinization and the average salt content in the soil layer (%, the percentage of soil quality), the saline soil may be further divided into four categories [63], as shown in Table 3.

Table 3. Detailed classifications of saline soils used engineering based on the degree of soil salinization [63].

Type of Saline Soil	Average Salt Content of Saline Soil Layer (%, as a Percentage of Soil Mass)			
	Chlorine Saline Soil	Chlorite Saline Soil	Sulfite Saline Soil	Sulfate Saline Soil
Weak saline soil	0.3~1.5	0.3~1.0	0.3~0.8	0.3~0.5
Middle saline soil	1.5~5.0	1.0~4.0	0.8~2.0	0.5~1.5
Strong saline soil	5.0~8.0	4.0~7.0	2.0~5.0	1.5~4.0
Exceed saline soil	>8.0	>7.0	>5.0	>4.0

According to Table 1, the contents of soluble Cl^- and SO_4^{2-} within the SRS of Tianjin Port were about 8.36% and 0.188%, respectively. The relative contents of Cl^- and SO_4^{2-} were confirmed by Equation (1) as $m_{C\text{-}S} = 44.47$, and the salt content for the soda residue after undergoing drying was about 13.88% [63]. On the basis of the data presented in Tables 2 and 3 and the location of the SRS, the Tianjin Port soil can be classified as coastal excessive-chlorine saline soil.

Due to the internal pore structure, the high moisture content and the 2–3 times higher soluble Cl^- content in SRS compared to that in the ocean environment, RC structures built on such SRS will be subjected to rapid invasions by high concentrations of Cl^- ions, inducing accelerated corrosion of their rebars and further shortening their service life. However, there is no literature report on achievements related to improving the durability of RC structures that are exposed to coastal SRS. Thus, it is necessary to carry out some exploration of this vital issue in order to provide theoretical and technical support for the durability design, evaluation and maintenance of RC structures built in such settings.

3. Literature Review Exploring the Influence of Saline-Soil Corrosive Environments on RC Structure Durability

According to the analysis presented in Section 2, the sampled SRS was classified as a coastal excessive-chlorine saline soil. In Section 3, the influence of this soil environment on the degradation and durability of RC structures is reviewed in order to lay a foundation for future research.

3.1. Deterioration of RC Structures in Saline Soil Corrosive Environments

The Dagang power plant in Tianjin, China, was built in a coastal saline-soil area. Its main box-type RC structure was eroded by various corrosive ions, but mainly Cl^-, from the soil, which led to serious damage after only eight years [64]. At the power plant, rust expansion and cracking along the tendons of RC square piles within 0–0.4 m of the mud surface were observed; the maximum crack width was as high as 5 mm, and the maximum spalling depth was as high as 18 mm [58]. Serious corrosion of the rebars in the RC square columns, cracking of concrete protective layers and large-scale erosion and shedding of concrete at the corner of the columns occurred in three highway bridges built on coastal saline soil in Tianjin after only 8–10 years. Erosion due to the presence of corrosive salts within the saline soil, especially Cl^-, was not considered during the design and construction process, as shown in Figure 5a.

At the saline-soil area in Qarham, Qinghai Province, China, RC structures such as transmission tower foundations, telegraph pole foundations, walls and other important RC components, were produced without special anti-corrosion treatment. After about 1–4 years, phenomena including rebar corrosion, concrete rust swelling, cracking and the covering layer falling off appeared at the adsorption area near the root of these structures [61,65], as shown in Figure 5b–d. Due to the severe corrosion caused by the saline soil and water erosion in salt-containing environments, the RC buildings in southern Xinjiang have suffered from different degrees of durability diseases, including concrete cracking and spalling and even rebar corrosion (Figure 5e,f), which means that their service life will be much lower than that estimated in the design phase. As such, the repair, reinforcement, demolition and even reconstruction required for RC structures are consuming a lot of manpower, material and financial resources [66–68]. The corrosion damage to concrete and RC buildings exposed to saline-soil environments in the Hetao area of Inner Mongolia is also serious [69], as shown in Figure 5f.

In summary, the long-term exposure to saline soil has a significant influence on the damage and deterioration of RC structures, greatly threatening their durability and shortening their designed service life. By analyzing the deterioration phenomena of RC structures exposed to such corrosive environments, the importance and urgency of investigating the durability of RC structures in such settings are further demonstrated.

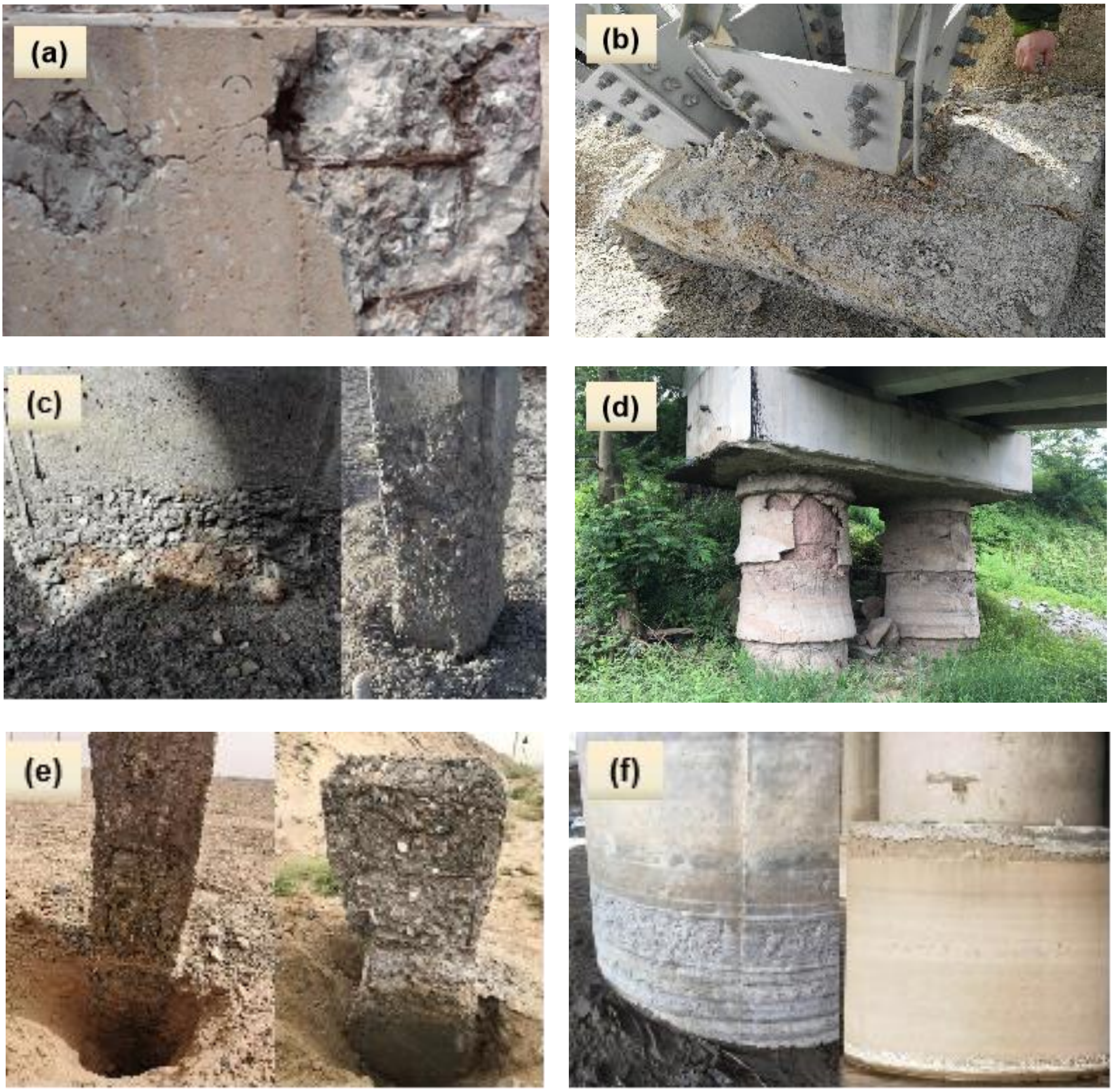


Figure 5. Deterioration of reinforced concrete (RC) structures due to saline-soil corrosion in different areas of China: (**a**) RC stand column in a coastal area of Tianjin city, China [70]; (**b**) transmission tower RC foundation in Qarhan area, Qinghai Province, China [61]; (**c**) RC stand column in Qarhan area, Qinghai Province, China [61,65]; (**d**) RC bridge pier of Tarim River, Xinjiang, China [66]; (**e**) RC boundary monument in Hotan area of Xinjiang, China [66,68]; (**f**) RC bridge pier in Hetao area of Inner Mongolia, China [71].

3.2. Advances in the Durability of RC Structures in Saline-Soil Corrosive Environments

Wang et al. [54], Li et al. [70], Lin et al. [72] and Man et al. [73] summarized the advances in the durability of RC structures in saline-soil environments achieved by domestic and foreign scholars before 2013, 2015, 2017 and 2019, respectively. They focused on the influences of a single factor (chloride, sulfate, etc.) and multiple factors (composite salt) on the corrosion of RC structures, as well as on the damage and degradation mechanisms of RC structures, ion intrusion into RC buildings, the ion transport model and the rebar corrosion mechanism, etc. These were summarized for chloride, sulfate and composite saline soil environments. These reviews promote the development of durability research for RC structures, which will have important scientific significance and value for engineering. On this basis, this paper reviews the advances in recent years in improving the durability of RC structures in saline soil environments (especially chlorine saline soil).

Qiao et al. [74] compared the distribution of Cl^- concentrations at a soil depth of 3 m in saline soil in the Qinghai Lake, Tianjin coastal and Lianyungang areas and pointed out that the Cl^- concentrations near the soil surface reached the maximum due to the strong evaporation of water near the soil surface. They found that the Cl^- content within saline soil gradually decreased with an increase in soil depth and showed semi-parabolic distribution characteristics, as shown in Figure 6. Therefore, for RC structures built on saline soil, rebars at the position of highest Cl^- concentration (i.e., semi-buried, near the surface) usually suffer from corrosion. It was found that the corrosion of semi-buried RC structures in the adsorption zone was most serious in saline soil environments [58,74,75]. Leng et al. [58] investigated the durability of semi-buried RC square pile specimens exposed to coastal saline soil in Tianjin, China, for 17 years. It was pointed out that the rebar corrosion was most serious in the adsorption area at around 350 mm from the ground surface. The weight loss rate of the rebars exceeded 2%, and the corrosion depths exceeded the thickness of the covering layer. Additionally, may RC components failed and were destroyed. Zhang et al. [75] focused on RC structures exposed to saline soil environments along the Chage highway in Qinghai Province, China. They carried out an accelerated corrosion test for concrete under alternate wetting–drying cycles with chloride salt using a simulated solution test method, in which solutions with the same corrosive ion concentrations as those of the saline soil were created to simulate the saline soil and groundwater corrosive environment. The chloride ion concentration profile for concrete specimens in the adsorption area was investigated, and the transport mechanism allowing for chloride ion exchange between the semi-buried concrete and saline soil was revealed: the external transport mechanisms were found to be the evaporation–concentration and capillary adsorption of chloride ions, while the internal mechanism was mainly chloride diffusion, as shown in Figure 7. Finally, the service life of concrete structures exposed to saline soil was predicted based on the chloride profiles.

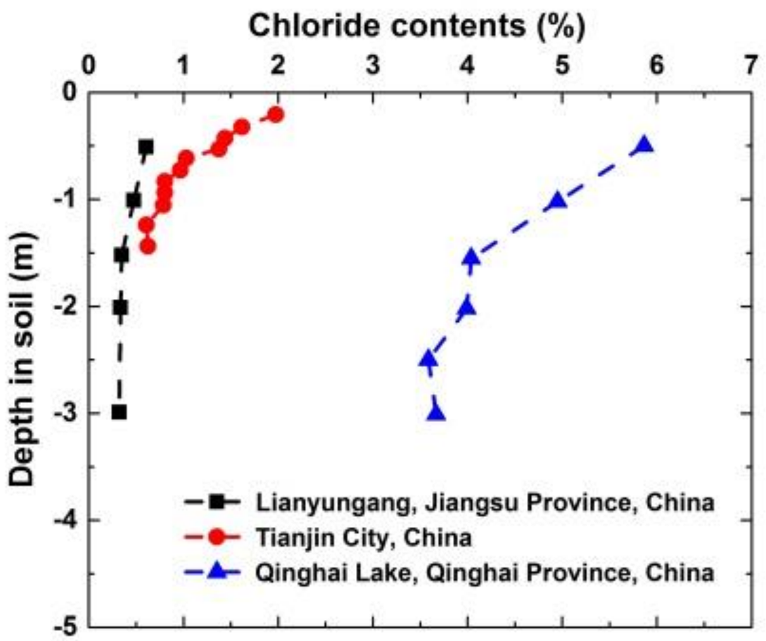


Figure 6. Chloride content distribution with depth in saline soil.

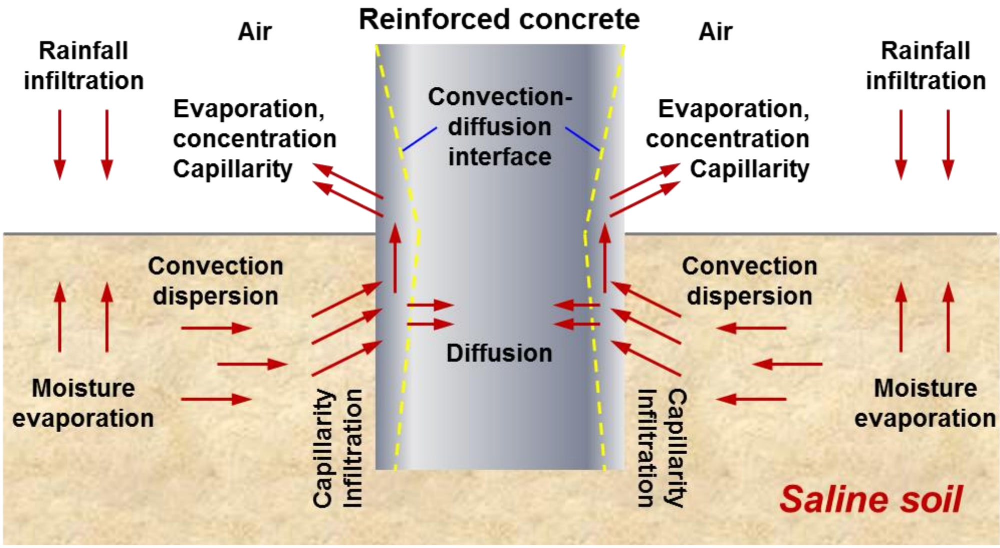


Figure 7. Chloride transport mechanism between semi-buried concrete and saline soil.

Sun [76], Qiao et al. [77] and Qiao et al. [78] investigated the coupling effect of multiple damage factors on concrete durability in the saline soil environment of the Tianshui region of Gansu Province, in Ningxia Province, and in the Xining region of Qinghai Province using an outdoor buried test and indoor simulated salt solution test. In this way, the damage deterioration mechanisms for the concrete microstructure were revealed. On this basis, the authors [79] placed magnesium cement concrete specimens in the saline soil environment of Qinghai Province to carry out a field exposure test. The improvement effects of magnesium cement on concrete durability in saline soil environments were investigated. Subsequently, the optimal mix proportion of magnesium cement concrete was quantified [80]. Moreover, the corrosion behavior of coated rebars embedded in magnesium cement RC were clarified by an immersion test in a simulated chloride solution [81,82]. On the basis of the unitary Wiener degradation process, a reliability model for concrete in saline soil areaa was established and the structural service life was predicted [83]. Uniting the XRD, SEM and other technologies, the damage and deterioration mechanisms of concrete exposed to a saline soil environment were revealed at a microscopic level [81–83]. Additionally, Yan et al. [84] used an indoor simulated solution test, microscopic test technology and theoretical models to investigate the chloride diffusion characteristics of concrete exposed to saline soil from Qinghai. The microscopic morphology characteristics of the concrete surface were revealed, and the service life of RC structures in such soil was predicted. According to the long-term measurements for concrete immersion in a simulated chloride solution, a probability model of steel corrosion for RC structure was established, and the influence of covering layer thickness on steel corrosion probability was clarified. Additionally, Based on experimental tests, a model of Fick's second law, the Monte-Carlo method, the BP neural network method, etc., a service life prediction model for RC structures in a saline soil environment was established [85–87]. Wu et al. [88] pointed out that the presence of Cl^- in soil can reduce the transport capacity of SO_4^{2-} within concrete, i.e., the higher the Cl^- concentration, the more obvious the inhibition of sulfate diffusion.

Using numerical simulation technology, Gao et al. [89] investigated the chloride migration characteristics in concrete exposed to a saline soil environment considering the effects of the electromigration field. In this way, the binding and capillary actions and a chloride ion transport coupling model for concrete were established. Liao et al. [90] carried out an ion invasion experiment in concrete under the conditions of Cl^- and SO_4^{2-} coexisting in saline soil at the southern edge of the Xinjiang Junggar Basin. In this way, the anti-salt ion-intrusion characteristics of concrete materials in a saline soil environment were revealed. The diffusion laws for various corrosive ions in concrete under alternate drying–wetting cycles in saline soil areas in northwest China were investigated using the simulated solution test method [91]. It was found that the diffusion behaviors of Cl^- and SO_4^{2-} obeyed Fick's second law. On this basis, a Cl^- and SO_4^{2-} diffusion model was established, considering the proportion parameters of the concrete mixture. A field long-term exposure test for RC short columns in a saline soil area was carried out by Wang and Zhang [92], and the degradation trends of RC column components were revealed using electrochemical and ultrasonic methods combined with the three-parameter Weibull function theory. Meng et al. [93] used soil samples from the severely saline soil area of Geermu, Qinghai Province, China, as electrolytes to carry out an electric-accelerated corrosion test for RC specimens. Those authors subsequently evaluated the corrosion deterioration behavior of RC specimens in such a saline soil environment. Based on the parameter estimation of the Weibull distribution, a damage deterioration model was established. The authors pointed out that the corrosion failure of the rebar and concrete damage were the leading factors of RC structure deterioration in the early and late stages, respectively.

In summary, pre-existing research methods, technical approaches and the results reported in the literature on the durability of RC structures in saline soil environments in China can provide important support and have significance for further explorations of the durability of RC structures exposed to SRS environments in the coastal areas of China.

3.3. Measures to Improve the Durability of RC Structures in Saline Soil Environments

The sulfate and chloride resistance of ordinary Portland cement and high-sulfate-resistant Portland cement concrete of different strength grades exposed to a soil environment in which chloride and sulfate coexisted was investigated by Chen et al. [94]. It was suggested that the durability of RC structures in such environments can be effectively improved through the introduction of high-performance concrete materials that exceed the strength of C40. Wang et al. [95] proposed improving the durability of concrete structures in saline soil environments in southern Xinjiang by using high-performance anticorrosive coatings, increasing the concrete density, inhibiting rebar rust, using a waterproof belt and impervious membrane, etc. Da [96] presented effective measures to protect the external surface of RC structures and discussed the addition of admixtures in internal concrete materials to improve the durability of RC structures in the saline soil environment of Qaidam Basin in Qinghai Province, China, mainly considering the effects of chloride and sulfate. Cao et al. [97] designed six kinds of concrete mix proportions, i.e., single-, double- and triple-added fly ash (FA), GBFS and silica fume (SF). By means of a simulated solution drying–wetting cycle corrosion test, XRD, SEM and other approaches, the authors showed that the chloride salt and sulfate resistance of the concrete increased with an increase in admixture content, and that the effect of FA was notably better than those of other admixtures (GBFS and SF). Wei et al. [98] and Yuan et al. [99] investigated the effect of mineral admixture on the resistance of concrete to saline soil under the conditions of insufficient wet-curing using 28 d compressive strength analysis, chloride ion permeability resistance, sulfate resistance and connected porosity of concrete, etc. The results indicated that the resistance of concrete can be effectively improved by mixing superfine/ordinary slag. Yang [100] investigated the durability improvement measures for RC materials and the internal corrosion resistance technology of concrete in a saline soil environment in the Hexi area in Gansu Province, looking at raw materials, additives and the admixture and mixing ratio.

The distribution of saline soil and its corrosive characteristics regarding RC structures in western Tianshan, Kunlun Mountains and the central plain of Tarim Basin in Xinjiang were revealed in [101]. The authors of that paper proposed and summarized effective anti-corrosion measures for transmission-line tower infrastructures. These achievements have significance for RC structures in practical engineering construction. According to an in situ exposure test and indoor accelerated experiment, Cao et al. [66] proved that the deterioration-resistance ability of basalt fiber-reinforced concrete against compound salt increased with an increase in fiber content. This knowledge was notably applicable in saline soil environments and extreme arid desert climates such as those in southern Xinjiang, China. The mechanical performance and crack resistance of concrete mixed with FAs and slags in saline soil environments under large temperature fluctuations were investigated by Lu et al. [102]. The results showed that the density and pore structure of concrete were effectively improved by the addition of 15% FA and 20% slag, while the crack widths of concrete were significantly reduced. Using field tests and SEM technology, Ma et al. [103] investigated the effect of FA content on the compressive strength of concrete in a saline soil environment in Ping'an District, Haidong City, Qinghai Province, China. The authors pointed out that the additional FA helped to improve the concrete compressive strength; the optimal content of added FA was found to be almost 10%. Adopting the XRD method, Liao et al. [104] investigated the influence of saline soil on the corrosion and degradation of RC structures in the Hotan area of Xinjiang, China. Scholars have suggested that cement with $w/b < 0.4$, FA, SF and other admixtures, supplemented with steam curing, can be utilized to cast the concrete, effectively enhancing the durability of RC structures exposed to saline soil environments.

In summary, a series of effective measures, including improvements in concrete strength, reductions in the water–binder ratio, the addition of mineral admixtures and fiber reinforcements, etc., can be adopted to enhance the durability of RC structures in saline soil environments. These measures can help to lay vital foundations and have significant value for durability enhancements of RC structures exposed to the corrosive coastal SRS environments.

4. Results and Discussion of Durability Issues of RC Structures in Coastal SRS Environments

The SRS in coastal areas in China typically has a large area, high volume, large range, high moisture content, high chloride ion content and deep-thickness foundation. Corrosive ions, mainly Cl^-, within the pore solution of coastal SRS intrude into concrete through multiple transport mechanisms, resulting in performance deterioration of RC materials, i.e., by inducing rebar corrosion, and eventually causing durability failures. However, to date, no literature report has been published on the durability issues faced by RC structures, especially the deterioration of such structures caused by chloride ions which are abundant in coastal SRS environments. Through a comprehensive analysis, the most significant issues regarding the durability of RC structures in coastal SRS which require urgent investigation are summarized as follows:

(1) The transport mechanism and prediction model of corrosive ions dominated by Cl^- in SRS and RC structures require in-depth investigation.

Chloride ions intrude into concrete and induce rebar corrosion. This was demonstrated to be the main cause of durability failures in RC structures in coastal corrosion environments. Thus, this is the first significant issue that we should explore, as it is essential to reveal the transport mechanisms of corrosive ions in RC structures and further establish a Cl^- transport model for concrete considering multi-factor coupling effects.

(2) The deterioration mechanism of RC materials in coastal SRS environments needs to be further examined.

Although the Cl^- content is particularly high in SRS, many other kinds of corrosive ions, including SO_4^{2-} and Mg^{2+}, are present. The damage and degradation mechanisms of RC upon exposure to multiple ions are still unclear. Hence, this is the second significant issue: we should investigate the influence of multi-ion intrusion on the macroscopic properties and microstructure of RC materials in order to reveal the degradation mechanism of RC composites in coastal SRS corrosion environments.

(3) The long-term performance reduction process of RC components in coastal SRS corrosion environments requires elaboration.

The time-dependent performance degradation of RC components due to the intrusion of corrosive ions is unknown. This is the third significant issue: we should establish a quantitative index for evaluating the degradation degree of RC components in SRS environments. On this basis, an in-depth exploration should be carried out regarding the long-term performance reduction process of RC components.

(4) A durability design theory for RC structures needs to be established, considering the effect of the intrusion of multiple corrosive ions into concrete.

Durability design theory for RC structures refers to the safety design theory that considers variations in the structural-bearing capacity according to service time during the whole life-cycle. There has been no research on the variations that occur when RC structures are exposed to coastal SRS environments. Therefore, the fourth significant issue is the need to establish such a durability design theory, considering the intrusion of multiple corrosive ions, RC material deterioration and evolution in structural bearing-capacity.

(5) Effective enhancement measures should be proposed to improve the durability of RC structures in coastal SRS corrosive environments.

To comprehensively study the mechanical properties, anti-ion permeability, impact on the ecological environment, etc., of RC materials, we should focus our attention on enhancement measures to improve the durability of RC structures exposed to saline soil environments, as discussed in Section 3.3. The fifth significant issue is the need to explore the influences of mineral admixture types, proportions and percentage of substituted cement, etc., on the durability of RC structures to obtain the optimal mineral admixture parameters and propose effective engineering–technical measures to improve the durability of RC structures in coastal SRS environments.

The results of the present study will help to promote the development of theoretical research on RC structure durability in coastal corrosive soil environments, as this would be of important scientific value and would make up for the research gap regarding the durability of RC structures in such settings.

5. Conclusions and Future Works

This paper focused on the vital issue of RC structure durability, as affected by corrosive ions, dominated by the intrusion of chloride ions into concrete exposed to coastal SRS environments. Firstly, SRS was classified as coastal excessive-chlorine saline soil, according to an analysis of the quantitative relationships of the corrosive ions present in SRS. On this basis, deterioration in RC structures in China was elaborated and advances in RC structure durability were reviewed. Through a comprehensive analysis, the vital issues that should be investigated regarding the durability of RC structures exposed to SRS environments were revealed. Some useful conclusions are as follows:

(1) The soda residue used as an engineering foundation soil can be classified as coastal excessive-chlorine saline soil, based on its soil properties. The internal pore structure for SRS is well-developed and its moisture content is very high compared to that of general soil. The soluble Cl^- content within the pore solution of SRS is almost 2–3 times higher than that of the marine environment. RC structures built on SRS are subjected to rapid invasion by high concentrations of Cl^- ions, which induces accelerated rebar corrosion and shortens the durability service life of such structures.
(2) According to our review of the advances in the durability of RC structures in saline soil environments in China, the importance and urgency of durability issues are further demonstrated. A number of useful methods, technical approaches, significant achievements and improvement measures reported in the literature can help us to provide vital support for further exploration of the durability of RC structures in coastal SRS environments.
(3) In view of the threat to RC structures caused by coastal SRS in China, the durability of such structures should be urgently investigated. Investigations can be divided into three aspects, namely, materials, components and structures, covering the transport

mechanisms and prediction models of corrosive ions dominated by Cl^- in RC, the deterioration mechanisms of RC materials, long-term performance evaluations of RC components, durability design theory for RC structures considering the effect of the intrusion of multiple corrosive ions into concrete, and enhancement measures which are needed to improve the durability of such structures. These are clear research directions for the development of a basic theory of RC structure durability in coastal SRS environments.

Through the research presented in this paper, the adverse effects of coastal SRS on the durability of reinforced concrete structures have been clarified, and five significant issues requiring urgent investigation have been identified. It should be noted that research to address the five aforementioned problems is currently under way or has not yet been carried out. In our follow-up work, we will focus on these important issues in order to promote the development of theoretical research on RC structure durability in coastal corrosive soil environments, as this would be of important scientific value and would make up for the research gap regarding the durability of RC structures in such settings.

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