Study on Cl\(^-\) Erosion of Concrete under the Combined Effect of Fatigue Load and Wet–Dry Cycles: A Review

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Abstract: The service environment of concrete in the marine environment is harsh, and demands regarding the durability of marine concrete have increased. Marine concrete in harbor and wharf areas suffers from the combined effect of fatigue load, dry–wet cycles, and Cl\(^-\) erosion, which can result in spalling of the concrete surface, corrosion of the internal reinforcement, and even concrete damage. This paper reviews recent research results on the durability of concrete and reinforced concrete (RC) under the combined effect of fatigue load, dry–wet cycles, and Cl\(^-\) erosion. We further assess the variation in Cl\(^-\) transport properties with fatigue load, the causes behind the reduction in the carrying capacity of RC products under fatigue load, the methods of Cl\(^-\) erosion on concrete under the pressures imposed by dry–wet cycles, and the damage of the protective layer of concrete due to accelerated Cl\(^-\) erosion caused by the action of dry–wet cycles. Further studies are needed on the durability of concrete under the action of fatigue load, wet and dry cycles, and Cl\(^-\) erosion, in addition to the testing of the durability of concrete under the combined effects of the afore-mentioned various factors.

Keywords: marine concrete; durability; fatigue load; wet and dry cycles; Cl\(^-\) erosion; coupling effect

1. Introduction

In recent years, with the development of marine resources and the utilization of the marine space, the demand for marine structures has steadily increased. As an excellent building material, concrete is widely used because of its low cost, and it is the preferred material used in complicated environments. Studies have shown that chloride ion (Cl\(^-\)) corrosion was the first problem encountered by concrete structures in the marine environment [1–3]. During the service process, marine concrete is subjected to a combination of external loads and environmental factors. For example, concrete from the harbor and dock are subjected to the action of fatigue load, dry–wet cycles, and Cl\(^-\) erosion.

On the one hand, the durability of concrete in the harbor and wharf is obviously affected by the fatigue load, and the increasing stress level of the fatigue load causes the formation of cracks in concrete, resulting in a reduction in the bearing capacity of the concrete structure. Consequently, researchers have investigated the durability of concrete under the action of fatigue load and Cl\(^-\) erosion. On the other hand, reinforced concrete (RC) in the splash and tidal zones is exposed to an environment of dry–wet cycles, and the corrosion damage of concrete products is the most serious, which has become the key protection area for the durability design of harbors and wharfs. In order to improve the service life of RC structures, researchers are currently researching RC durability under the action of Cl\(^-\) erosion and dry–wet cycles.

Currently, research on the sustainability of concrete environments exposed to Cl\(^-\) primarily includes two avenues. One is to establish a model and use numerical analysis to study the durability of concrete under fatigue load and Cl\(^-\) erosion, mainly to study the transmission mechanism of Cl\(^-\) in concrete and the durability of RC after the corrosion of...
reinforcement caused by Cl\(^-\). The other is a durability test conducted in the laboratory or marine test base, but durability tests require long processing times and the loading device design is complex, so there are relatively few test studies on the coupling action of fatigue load and environment factors. There are even fewer studies on the combined effect of fatigue loads, dry–wet cycles, and Cl\(^-\) erosion, with most studies using alternate testing of fatigue load and dry–wet cycles, which does not reflect the durability problems faced by concrete in the actual marine environment under the action of fatigue load, dry–wet cycles, and Cl\(^-\) erosion.

2. Coupling Action of Fatigue Load and Cl\(^-\) Erosion

For fatigue load and Cl\(^-\) coupling tests, most studies have focused on physical and structural prospects. Studies have combined analysis of the physical side with the fine structure of concrete and concentrated on the Cl\(^-\) transport property in concrete, while regarding the structural side, they have focused on the corrosion of reinforcement in concrete, the bonding properties of the reinforcement and concrete, and the carrying capacity of concrete products.

2.1. Transport Properties of Cl\(^-\) under Fatigue Loading

There are two types of fatigue load: by compression or flexion. The stress level of fatigue load is the ratio of the actual stress applied to the breaking strength and is an important factor affecting the effect of fatigue load. The diffusion rate and the Cl\(^-\) content in concrete under various fatigue loads are, thus, different \[4\].

Under the coupling effect of compressive fatigue load and Cl\(^-\), the change in the pores and the diffusion of Cl\(^-\) into concrete are directly related to the stress level of the compressive fatigue load. Ba \[5\] and Zhang \[6\] conducted compressive strength tests at various stress levels and clearly observed the effect of the stress level on the diffusion coefficient of Cl\(^-\). After applying compression fatigue load (for five times, the stress level was equal to 0.4 times the level of compressive strength), the resistance to Cl\(^-\) permeability was reduced; after applying compression fatigue load (for five times, the stress level was equal to 0.8 times the level of compressive strength), the resistance of concrete to Cl\(^-\) permeability was further reduced, and it showed that the fatigue load significantly reduced the Cl\(^-\) resistance of concrete. The degree of stress had a direct effect on the transport of Cl\(^-\) in the concrete. The greater the accumulated fatigue damage, the more severe the deterioration of the concrete’s durability and the higher the Cl\(^-\) diffusion coefficient. Sun \[7\] found that the compression fatigue load increased the velocity and depth of the diffusion of Cl\(^-\). When the stress level of the compression fatigue load did not exceed 0.4 times the level of compressive strength, the effect on the Cl\(^-\) diffusion rate and depth was small, while the Cl\(^-\) diffusion rate and depth increased significantly when the stress level exceeded 0.6 times the level of compressive strength. Liu et al. \[8\] also reported the results of tests conducted with a critical stress level of 0.4 times the level of compressive strength. When the stress level of the fatigue load applied to concrete was lower than the critical stress level, the damage was smaller, the stress level was greater than the critical stress level of the concrete, and the free Cl\(^-\) content at a certain depth in the concrete was significantly increased. The higher the stress level, the greater the Cl\(^-\) content at the same depth in the concrete. Wang et al. \[9\] considered that Cl\(^-\) erosion on concrete mainly relies on the permeation of water through pores. They studied the diffusion law using a pore solution in concrete under specific stress levels and compression fatigue conditions, and it was found that the increase in stress level and amount of fatigue leads to the development of microcracks, which increases the efficiency of water transfer in concrete and thus leads to an increase in the Cl\(^-\) diffusion coefficient. At low stress levels, the compressive fatigue load can interfere with Cl\(^-\) erosion. In the study of the effect of uniaxial compressive stress on the porosity of cement paste, Pons et al. \[10\] found that the fatigue load not only did not cause damage to the concrete microstructure, but also acted as a dense porous
material, making it difficult for the solution to penetrate into the concrete, thus decreasing Cl\textsuperscript{−} diffusivity.

In the bending fatigue test, the stress level and fatigue count also influenced the durability performance of the concrete. Ren et al. [11] pointed out that the bending fatigue load reduced the Cl\textsuperscript{−} resistance of concrete, while the bending fatigue load increased the Cl\textsuperscript{−} diffusion rate, which increased significantly after a stress level greater than 62% of the tensile strength. The service life of concrete structures is shortened due to the coupling effect of the bending fatigue load and Cl\textsuperscript{−}. Li [12] found that, when concrete was exposed to a low stress level, the Cl\textsuperscript{−} diffusion coefficient of concrete first decreased, which was due to the extrusion of pores at a low stress level, but the Cl\textsuperscript{−} content inside the concrete increased significantly and Cl\textsuperscript{−} resistance decreased as the stress level and the amount of fatigue increased in the concrete.

In contrast to the compression fatigue load, the bending fatigue load is not the same in the tensile and compression areas of concrete. Niu et al. [13] concluded that bending fatigue load caused damage to the concrete interior and decreased the anti-Cl\textsuperscript{−} erosion performance of concrete, and the free Cl\textsuperscript{−} content in concrete increased with the increase in fatigue damage variability. The free Cl\textsuperscript{−} content in the concrete tension zone was higher than that in the compression zone after fatigue damage, and the damage in the concrete tension zone was more severe than that in the compression zone under the same stress level.

The effect of fatigue load on the durability of concrete has been attributed to changes in residual strain. Wang et al. [9] observed that compressive fatigue load had a significant effect on residual strain, and the concrete was subjected to compressive fatigue damage through residual strain in three stages; concrete damage accumulated more rapidly as the residual strain increased. Nakhii et al. [14], Gontar et al. [15], and Tran et al. [16] concluded that the Cl\textsuperscript{−} permeability of concrete after fatigue load also mainly depends on the residual strain of concrete, which gradually increases as the residual strain increases. The stress level required, when the Cl\textsuperscript{−} permeability of concrete started to increase significantly after unloading by multiple fatigue loads, was lower than that of concrete after unloading by one load, which is consistent with the gradual accumulation of internal damage in concrete under fatigue load. Jiang [17] and Sun [18] studied in detail the relationship between the residual strain and Cl\textsuperscript{−} diffusion coefficient of concrete under bending fatigue load and Cl\textsuperscript{−} coupling, and they found that the Cl\textsuperscript{−} diffusion coefficient increased after the residual strain increased. Figure 1 shows the variation of Cl\textsuperscript{−} diffusion coefficient with residual strain for (a) plain concrete and (b) High-Performance Concrete (HPC) and High-Performance Fiber-Reinforced Cement Composite (HPFRCC). The Cl\textsuperscript{−} diffusion coefficient increased significantly after the residual strain reached a certain critical value. This critical value was identified as the starting point for the concrete resistance to Cl\textsuperscript{−} diffusion.

![Figure 1](image-url)  
**Figure 1.** Comparison of Cl\textsuperscript{−} diffusion coefficients in concrete for different degrees of flexural fatigue damage (a) plain concrete; (b) HPC and HPFRCC [17,18].

Some researchers conducted a numerical analysis of the microstructure of fatigue load in concrete. Based on the study of concrete fracture mechanics, Horii et al. [19] investigated
the mechanism of fatigue crack growth under cyclic loading and observed a slow crack expansion rate at low stress levels. As the strain level increased, the crack dilation rate increased. Gérard et al. [20] concluded that the cracks generated by the fatigue load had a greater effect on the pore size of the concrete around them, and if there were continuous cracks, the effect of penetration would be greater than that of diffusion.

Cl$^-$ erosion has been incorporated into concrete fatigue loading models to study the durability of concrete. Xu [21] concluded that the permeability of concrete at low stress levels that produce deformation was closely related to concrete pores and found that it was the initial porosity of concrete that was the main cause of Cl$^-$ diffusion. As the stress level increased, it was only after the increase in micro-scratches in the concrete and their penetration that the diffusion of Cl$^-$ was associated with fatigue. Yang [22] proposed a novel theoretical model for simulating the migration process of Cl$^-$ under bending fatigue load and concluded that the amount of the fatigue load affects the intrusion depth of Cl$^-$.

The occurrence of fatigue loads affects the Cl$^-$ content. Xiang [23] described the fatigue damage evolution process of concrete with a model and analyzed the durability of a highway concrete bridge with fitted calculations. It was found that the Cl$^-$ content in concrete at the early stage of fatigue was basically equal to the Cl$^-$ content in concrete under fatigue load, but with the increase in fatigue load stress level and amount of fatigue, the Cl$^-$ content in the concrete’s surface layer increased significantly.

There are parallels and variations between the effects of compressive fatigue load and flexion fatigue load on the durability of concrete. The similarity lies in the fine structure, but both cause microcracks and change the pore structure of concrete. The difference is that the bending fatigue load in concrete is different on the compressive and the tensile zones; the compressive zone of concrete in the early stage of fatigue loading is closer to the low stress level of concrete under compression fatigue loading state. When the durability of concrete was studied after adding Cl$^-$ erosion to the fatigue load, the Cl$^-$ diffusion was not obvious at low stress levels, while the Cl$^-$ diffusion rate increased as the fatigue load stress level and the amount of fatigue increased, which was due to the microcracks in concrete caused by fatigue load, providing a channel for Cl$^-$ transport and eventually accelerating the reduction in the concrete’s performance to resist Cl$^-$ erosion.

2.2. Durability Performance of Reinforced Concrete under Fatigue Load Coupled with Cl$^-$

With the increase in corrosion problems in offshore structures in recent years, researchers have started to pay increasing attention to the effects of multiple factors acting together in the durability performance of RC, among which the most serious problem is caused by Cl$^-$. Cl$^-$ accumulates on the concrete surface and penetrates into the concrete pores, reaching the reinforcement surface and destroying the passivation film [24], which eventually leads to internal reinforcement corrosion as the erosion time increases. This corrosion reduces the cross-sectional area of the load bearing of the reinforced steel and the bonding capacity of the reinforced steel to the concrete, and it also leads to the cracking of the concrete’s protective layer after rusting and the expansion of the reinforced steel surface. After the fatigue load was applied, stress concentration occurred in the corroded part of the RC reinforcement, leading to a reduction in the load-carrying capacity of the RC and eventually to it reaching the end of its total fatigue life.

The effect of dynamic loading on the fatigue degradation of the RC was considerably greater than that of static loading. Ahn et al. [25] used the four-point static and dynamic deflection loading method in Figure 2 and obtained the conclusion that, compared with RC beams subjected to a static load, RC beams subjected to a dynamic load have a faster rate of corrosion of the reinforcement caused by Cl$^-$ intrusion, as well as a faster decrease in concrete load-carrying capacity by simulating the degree of corrosion of the reinforcement in the tidal zone of offshore structures under the combined effect of four-point bending fatigue load and an artificial seawater environment. Wu et al. [26] conducted an experimental study on the fatigue performance and Cl$^-$ permeability of RC beams and found that the fatigue load was more likely to cause Cl$^-$ to enter into the concrete than static loads.
Wang et al. [31] concluded that the load level directly affected the rate of the corrosion of reinforcement in concrete and stressed concentration in the reinforcement area, and the coupling of Cl$^-$ erosion and bending fatigue load accelerated the accumulation and development of damage. Zhou [28] found that the damage accumulation in the members with internal reinforcement corrosion under fatigue load was greater than that in the members with uncorroded reinforcement, and this damage accumulation was not a simple superposition relationship. Yuan [29] concluded that there was almost no difference in the load-carrying capacity between the columns with less Cl$^-$ corroded reinforcement and uncorroded columns under fatigue load, but in the RC columns with greater Cl$^-$ corrosion, the ultimate load-bearing capacity of the members was significantly reduced in RC columns with a higher degree of Cl$^-$ corrosion. Wu et al. [26] further considered the effects of reinforcement rate and working environment, and they found that the combined effect of initial fatigue damage and Cl$^-$ corrosion led to the corrosion of the tensile reinforcement, which greatly reduced the total fatigue life of RC beams. However, in other studies, such as [30], it was found that hoop reinforcement in re-cantilever piers under Cl$^-$ corrosion led to the corrosion of the tensile reinforcement, which greatly reduced the total fatigue life of RC beams. Fu et al. [32] also found that the presence of transverse fissures in the tensile surface of RC aggravated the corrosion of the reinforcements. Ordained et al. [33] found that the generation of longitudinal cracks was independent of both load stress level and load type, and they concluded that corrosion was not the only factor leading to the generation of cracks. The bonding capacity of reinforcement to concrete was then evaluated by studying the evolution of transverse cracks, and the stress level of bending fatigue load was determined. Zhou [28] also found that transverse cracks caused damage to the bonding properties of concrete and reinforcement.

It has been suggested that the fatigue load process leads to cracks in concrete structures, and the generation of cracks accelerates the corrosion of rebar steel in concrete. Wang et al. [31] concluded that the load level directly affected the rate of the corrosion of reinforcement within concrete, and that microcracks generated by the fatigue load had a greater effect on the corrosion of reinforcement in concrete than macro-cracks, but to some extent, micro-cracks could heal and reduce the corrosion. Jaffer [34,35] found that the Cl$^-$ invaded the interior of the concrete and corroded the armature, while the fatigue load led to the detachment of aggregates and cement paste from ordinary reinforced concrete (OPCC). Figures 3 and 4 show the three sites in OPCC and HPC where corrosion products enter the cracks. As shown in Figures 4 and 6, the opening and closing of cracks under fatigue load forced the flow of corrosion products from the reinforcement to the concrete bond into the cracks in OPCC and high-strength concrete (HPC) due to fatigue load. Thus, corrosion products diffuse from OPCC at the

Figure 2. (a) Static load test apparatus. (b) Fatigue load test apparatus [25].
cracks caused by fatigue load into the cement paste, while in fatigue-loaded HPC corrosion products stayed at the cracks at the reinforced concrete interface.

**Figure 3.** Distribution of corrosion products in dynamically loaded OPCC concrete (a) 9 mm from concrete surface; (b) 11 mm from concrete surface; (c) 13 mm from concrete surface. (Red arrows point to the location of visible corrosion products) [35].

**Figure 4.** Distribution of corrosion products in dynamically loaded HPC concrete (a) 10 mm from concrete surface; (b) 18 mm from concrete surface; (c) 20 mm from concrete surface (Red arrows point to the location of visible corrosion products) [35].

A numerical analysis was used to better study the causes of RC damage under fatigue stress and Cl\(^-\) erosion. Fang [36] established a microstructure model of rust products based on measured data and found that the coupling effect of chloride-salt–fatigue-load led to an increase in the content of rust products, which had a serious negative impact on the RC structure. The stiffener rust products also increased as the strain level of the fatigue load increased. The RC protective layer was more prone to cracking due to the coupling of fatigue load and Cl\(^-\) erosion, resulting in reduced durability. Rao et al. [37] proposed a simplified model for RC bridge columns with damage due to the Cl\(^-\)-induced corrosion of reinforcement, explaining the reduction in the cross-sectional area of reinforcement due to Cl\(^-\) corrosion. Similarly, it was found that the rate of reinforcement corrosion changed with different stress levels. Kurumatani et al. [38] combined fatigue damage modelling and crack extension analysis methods, followed by crack and Cl\(^-\) diffusion modelling of RC for steel corrosion studies and suggested that the future modelling of steel corrosion and corrosion cracking must be investigated experimentally and numerically. Lavorato [39] presented a numerical analysis of RC under bending fatigue load, where chloride corroded the reinforcing under fatigue conditions and ultimately affected the structural performance of concrete. Overall, the damage accumulation of RC under fatigue load was higher than that of the RC structure under a static load, and in the coupling of Cl\(^-\) erosion and fatigue load, cracks appeared on the surface of the RC structure under fatigue load to provide
space for Cl\(^-\) invasion. Cl\(^-\) then penetrated into the concrete and accumulated rapidly on the reinforcement surface to rust it. The expansion of rust products leads to cracks in the concrete structure, resulting in a decrease in the load-bearing capacity of the concrete structure, further accelerating the damage of the concrete structure.

3. Coupling of Dry–Wet Cycles and Cl\(^-\)

In the existing reports, it can be found that the concrete in the tidal and wave splash zone areas often show different degrees of damage, such as exposed reinforcement and spalling, mainly due to the coupling impact of dry–wet cycles and Cl\(^-\) erosion on concrete. Researchers have focused on solving the problem of concrete durability by the coupling of dry–wet cycles and Cl\(^-\) erosion, and research has also been focused on the study of the transport properties of Cl\(^-\) in concrete, as well as the study of the effect of Cl\(^-\) on reinforcement corrosion and the load-bearing capacity of RC structures under the coupled action of dry–wet cycles and Cl\(^-\) in RC members.

3.1. Transport Properties of Cl\(^-\) under the Action of Dry–Wet Cycles

Concrete under dry–wet cycles experiences repeated wet expansion and dry shrinkage, thus affecting its durability. Dry–wet cycles can directly change the pore structure of concrete to a certain extent, leading to the accumulation of internal cracks and eventually leading to a decrease in the permeability resistance of concrete. Zhang [40] found that hydration increased the internal compactness and strength of concrete at the start of the dry–wet cycles. Zhang [41] found that pores were the key to determine the permeability performance of concrete, and the pores that affect the permeability performance of concrete were mainly large capillary pores (100 nm–1000 nm), but as the dry–wet cycle time increased, the proportion of pores less than 100 nm in concrete increased. Arya [42] discovered that the quantity of Cl\(^-\) entering the concrete depends on the open porosity.

Unlike the free diffusion of ions in full immersion, the mode of transport in concrete in the dry–wet cycles state is divided into free diffusion, convection, and capillary action. The complex mode of transport also has different effects on the final Cl\(^-\) erosion results. Polder et al. [43] and Nielsen et al. [44] showed that the Cl\(^-\) erosion rate under the action of dry–wet cycles was significantly greater than that in the fully immersed concrete, with the difference increasing the longer the age of erosion and gradually decreasing as one moves deeper into the concrete. This suggests that the Cl\(^-\) erosion mechanism varies considerably in the concrete’s surface layer, while the erosion mechanism was closer in the deeper concrete. Shen [45] found that Cl\(^-\) accumulates rapidly in the early stage of dry–wet cycles, and as the number of dry–wet cycles increased, Cl\(^-\) accumulated in the concrete and combined with calcium ions. Eventually, CaCl\(_2\) precipitation could be observed in the internal pores and cracks.

The Cl\(^-\) distribution method in concrete during dry–wet cycles has been studied in depth. The change in Cl\(^-\) concentration in concrete with the increase in depth during wet and dry cycles increases first and then decreases, and the depth of this peak Cl\(^-\) concentration to the concrete surface is called the concrete convection zone [46,47]. Figure 6 shows the variation in free Cl\(^-\) content with depth for concrete with different water-to-ash ratios (w/c). Zhang et al. [46] found that concrete showed significant variation peaks in Cl\(^-\) content with depth during dry–wet cycles in both laboratory simulations and field exposure tests. The peak occurrence was attributed to the dry and wet cycles, and this location was also identified as the concrete convection zone. Chang [48] found that both dry–wet cycles of the specimens showed convective zone in the surface layer of concrete and found that, as a result of the dry–wet cycles, the convective zone was related to the total porosity, critical pore size, and open porosity. Zhang et al. [49] found that, while the convection zone was observed under dry–wet cycles and Cl\(^-\) erosion, the concrete convection zone gradually deepened with the increase in the number of dry–wet cycles, indicating that the migration of Cl\(^-\) to the inside of the concrete was accelerated under the action of dry–wet cycles. Lu [50] found that the convection zone was caused by the
simultaneous effect of Cl$^-$ scattering and convection, and that the depth of the convection zone increased the drying time. Xu [51] found that the transport depth under dry–wet cycle conditions was lower than that of full immersion, but the Cl$^-$ content at the same depth within the surface layer was greater than that in the full immersion case, and the generation of a convective zone was observed after ten dry–wet cycles. Figure 5 shows the variation in the surface Cl$^-$ content in concrete with depth for different dry–wet cycling regimes (refer to Table 1). Cl$^-$ generated a peak at 2 mm on the surface, identifying this region as the convective zone of the concrete.

![Figure 5. Transport properties of Cl$^-$ in concrete under different wet and dry regimes. (a) 30 times. (b) 40 times [51].](image)

**Table 1.** Dry–wet cyclic test system [51].

<table>
<thead>
<tr>
<th>Code</th>
<th>G1S1</th>
<th>G3S1</th>
<th>G5S1</th>
<th>G1S3</th>
<th>G1S5</th>
<th>QJPZ</th>
<th>DS-G5S1</th>
<th>DG-G1S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of dry and wet</td>
<td>1:1</td>
<td>3:1</td>
<td>5:1</td>
<td>1:3</td>
<td>1:5</td>
<td>5:1</td>
<td>1:5</td>
<td></td>
</tr>
<tr>
<td>Single time ratio/h</td>
<td>24:24</td>
<td>36:12</td>
<td>40:8</td>
<td>12:36</td>
<td>8:40</td>
<td>0:48</td>
<td>60:12</td>
<td>12:60</td>
</tr>
</tbody>
</table>

![Figure 6. Distribution curve of Cl$^-$ concentration in test concrete after days of exposure in a simulated environment (a) 200 d; (b) 600 d [46].](image)

Additionally, the effect of the dry–wet ratio and number of dry–wet cycles on Cl$^-$ erosion in concrete was not negligible. Both the wet and dry ratio and the number of cycles directly affected the process of Cl$^-$ transport. Hong et al. [52] found that, during drying, Cl$^-$ lodged deeper in the concrete remains in the saturated pore solution for free diffusion, and lengthening the drying cycle could accelerate Cl$^-$ infiltration. Drying led to the formation of crystalline compounds being adsorbed deeper, and after the next wetting cycle, Cl$^-$ increased in the concrete. Additionally, the infiltration rate was found to be linearly related to the square root of the number of dry–wet cycles. Sutrisno [53] also assessed the effect of wet and dry ratio on Cl$^-$ infiltration, with significant differences in
Cl\(^-\) concentration and depth within the concrete with different wet and dry ratios. Xu \[51\] observed that the convective area gradually disappeared as the number of wet and dry cycles increased in samples with a dry–wet ratio of less than 1. As shown in Figure 7, for each wet/dry ratio case at different cycle days, the Cl\(^-\) diffusion coefficient in specimens with a dry to wet ratio of \(\geq 1\) was slightly greater than that in specimens with a dry to wet ratio of \(<1\).

![Figure 7](image-url)  

**Figure 7.** Variation of Cl\(^-\) diffusion coefficient under different wet and dry cycle regimes \[51\].

At present, some results have been obtained from the numerical simulation of concrete subjected to Cl\(^-\) erosion under dry–wet cycle conditions domestically and abroad, and these results, in some cases, verified the conclusions obtained from the experiments and explained what was being microscopically observed. Recently, researchers \[47,54\] have provided a life expectancy for concrete structures in a dry–wet cycle environment. Oh \[55\], on the basis of Fick’s second law, examined the convective effect of moisture and derived convection–diffusion control equations that suit the model of ion transport inside concrete under the operation of dry–wet cycles more closely. Ababneh et al. \[56\] established the non-saturated state of concrete, and Soive \[57\] used an existing coupled ion-moisture transport model. After updating the relevant parameters in the model, it was highly consistent with the free and total Cl\(^-\) concentration curves measured in the laboratory under dry–wet cycles, avoiding the problem that the traditional Cl\(^-\) transport performance needed to consider porosity. Dong \[58\] designed a model to simulate the Cl\(^-\) diffusion in concrete under dry–wet cycles considering factors such as Cl\(^-\) concentration difference and convection and capillary action due to pore space, and they discussed the accuracy of the model in the context of practical situations.

\[
C(x, t) = C_0 + (C_{s,\Delta t} - C_0) \times \left[1 - erf\left(\frac{x - \Delta x}{2\sqrt{D(t)t}}\right)\right] \tag{1}
\]

\(C(x, t)\) is the chloride content at depth \(x\) and exposure time \(t\), \(C_0\) is the initial chloride content, \(C_{s,\Delta t}\) is the chloride content at depth \(\Delta x\) in the convective zone, \(erf()\) is the error function, and \(D(t)\) is the chloride diffusion coefficient.

Regarding the coupling effect of dry–wet cycles and Cl\(^-\), researchers have offered, through a combination of experimental and numerical analysis, a more detailed analysis of concrete during dry–wet cycles and the Cl\(^-\) erosion state of Cl\(^-\) transport. Most researchers concluded that the effect of Cl\(^-\) intrusion rate and concrete depth on wet–dry cycles was greater than under full immersion conditions. In order to further study the dry–wet cycle effect of Cl\(^-\) transport performance, researchers have studied the changes in the dry–wet ratio, but other conclusions of coupling effects were not presented.

### 3.2. Durability Performance of Reinforced Concrete under the Coupling Action of Dry–Wet Cycles and Cl\(^-\) Erosion

Dry and wet cycles allow Cl\(^-\) to enter RC and corrode the reinforcement, ultimately reducing the load-carrying capacity of RC. Ye et al. \[59,60\] found that dry–wet cycles favor the penetration of Cl\(^-\) into the concrete. Cl\(^-\) intrusion into the interior reinforcement surface did not directly cause reinforcement corrosion but accumulated at the reinforced concrete
interface until it reached a certain Cl$^-$ concentration, i.e., the critical Cl$^-$ concentration and rebar corrosion were accelerated [61–63]. As shown in Figure 8 [63], (a) the local corrosion of the reinforcement started, and the scanning electron microscope (SEM) was used to scan the corrosion site of the reinforcement, and it was observed that the triangular area in (b) was black corrosion products (Fe$_3$O$_4$), the elliptical area was red corrosion products (Fe$_3$O$_4$·xH$_2$O), and the rectangular area was the passivation film on the surface of the reinforcement. It can be seen that the formation of a protective film mostly on the surface of the reinforcement starts to be gradually replaced by corrosion products and the reinforcement gradually rusts. Kawasaki [64] used SEM to assess the coupling effect of dry–wet cycles and Cl$^-$ erosion to clearly observe reinforcement rusting and the loss of the oxide film of the reinforcement surface, followed by cracks around the reinforcement leading to the destruction of the concrete protective layer. Wei et al. [65] assumed that Cl$^-$ reaches the surface of the reinforcement at a constant rate, and a good linear relationship existed between the rate of reinforcement corrosion and the Cl$^-$ content at the reinforcement–concrete interface when the rate of reinforcement corrosion was low, from which a critical Cl$^-$ concentration could be deduced, which was not present for the reinforcement inside the already broken concrete. Wei [66] and Li [67] found that, as the number of dry–wet cycles in the case of Cl$^-$ corrosion increases, Cl$^-$ accumulates rapidly on the surface of the reinforcement and corrodes it rapidly, reducing the bonding properties between the reinforcement and the concrete, leading to a significant reduction in RC residual strength and ductility and a consequent decrease in the ultimate load-carrying capacity.

![Figure 8.](image_url)  
**Figure 8.** (a) Rusted condition of the reinforcement. (b) SEM morphology of the surface of the reinforcement at the rusted/unrusted junction [63].

The effect of fissures in reinforcement under wet–dry cycle was also considered [68]. Paul [69] comparatively studied the erosion of cracked and uncracked cementitious composites under dry–wet cycles and found that the depth of Cl$^-$ invasion was significantly higher in the cracked group than in the uncracked group, while the cracked group was more likely to cause the rusting of the reinforcement. Käthler [70] considered cracks as a favorable area for the initiation of corrosion under dry–wet cycles through which chlorides rapidly enter the concrete interior and concluded that the effect of Cl$^-$ on reinforcement in concrete under dry–wet cycles was greatly influenced by the relative humidity inside the concrete.

In addition to the corrosion of the reinforcements caused by Cl$^-$, the increase in the oxygen content during drying in wet–dry cycles also resulted in an increase in the corrosion rate of the reinforcements. Ahlström [71] found a direct relationship between reinforcement corrosion and relative humidity in RC and different rates of the corrosion of reinforcement at different relative humidity values because of the limitation of oxygen transport due to high humidity. Hussain [72] investigated reinforcement corrosion in concrete under dry–wet cycling conditions by means of a hypothetical relationship between Cl$^-$-corrosion-induced current changes in a variable humid environment and concluded that oxygen diffusion was an important factor affecting reinforcement corrosion during dry–wet cycling. Nishimura [73] examined the diffusion of oxygen and Cl$^-$ inside concrete during dry–wet
cycles: firstly, Cl\(^-\) accumulated on the surface of the reinforcing bars with diffusion, and when a critical amount of Cl\(^-\) concentrates in the reinforcement started to corrode it, and as the wet and dry cycles occurred, the oxygen content in the pores increased during drying, leading to the accelerated corrosion of the reinforcement. Kim [74] conducted a study of Cl\(^-\) erosion under dry–wet cycles using electrochemical methods and also found that the ion diffusion was intense during the wet phase and the corrosion rate of the reinforcement increased rapidly during the drying phase.

In addition to the environmental factors that require special attention when modelling the degradation of RC under the action of dry–wet cycles, the corroded state of internal reinforcement also requires attention [75]. In order to create a model of reinforcement erosion by Cl\(^-\) under timed conditions, Wang [76], in a study on the corrosion of reinforcing bars in RC under dry–wet cycles, found that the corrosion of the reinforcing bars was significantly increased with the increase in the crack width under timed conditions, which responded better to the reinforcement corrosion process as a result of the combined effect of dry–wet cycles and Cl\(^-\). Other researchers have simulated the durability of RC under dry–wet cycles and Cl\(^-\) erosion [77,78], and all of them compared these simulations with actual situations, but it was found that they could not be adapted to most numerical studies of the durability of RC under dry–wet cycles and Cl\(^-\) erosion.

The coupling effect of wet–dry cycles and accelerated Cl\(^-\) RC damage, as well as corrosion of the armatures, were more readily observed at the cracks rather than at other sites. In addition to the dry–wet cycles that make Cl\(^-\) penetrate rapidly into the concrete interior and lead to reinforcement corrosion, the presence of oxygen would also accelerate the reinforcement corrosion, while the drying process led to the evaporation of water in the pores, so that oxygen entered the interior of the pores to rust the reinforcement, and the corrosion rate of reinforcement was accelerated under the double corrosion effect, which eventually led to the loss of RC strength. In terms of numerical analysis, it could also reflect the damage of RC structure as a result of dry–wet cycles and Cl\(^-\) coupling, but there were still problems in trying to apply a single model to a wide range of applications.

4. Durability of Concrete under Dry–Wet Cycles, Fatigue Load, and Cl\(^-\) Erosion

The terminals of cross-sea bridges and harbors are subjected to traffic loads in a complex marine environment [79], and it is a challenge to completely simulate the actual service environment of marine concrete in the laboratory, yet the fatigue frequencies imposed on the concrete in the laboratory are 1 Hz. There is no clear specification reference for the dry–wet cycle regime in a chloride salt environment, but the specification for the dry–wet cycle test with reference to sulfate is 24 h for one cycle. It could be found that the time difference between one cycle of fatigue loading and one cycle of wet and dry cycle was large, and it was difficult to match in one cycle. Therefore, the existing studies mostly adopt the indirect study by alternate action, i.e., the fatigue post-concrete specimens are first subjected to dry–wet cycle tests with a chloride salt solution. The various experiments led to large variations in the study results, but also provided a reference for later studies.

The effects of each factor on the diffusion of Cl\(^-\) in concrete were apparent in the alternating dry–wet cycle and fatigue load tests. Fu [80] conducted fatigue tests first and subjected the concrete after fatigue completion to Cl\(^-\) erosion tests under immersion and dry–wet cycle conditions, and it was found that, as the stress level increased, the Cl\(^-\) infiltration rate increased, and the Cl\(^-\) infiltration rate of concrete with the same fatigue conditions under dry–wet cycles conditions was greater than that under full immersion conditions. Wu [81,82] experimentally investigated the effect of low fatigue load levels on the Cl\(^-\) diffusion rate of RC beams after 100 dry–wet cycles of seawater. As the stress level increased, the Cl\(^-\) diffusion rate also increased. Compared with RC without fatigue damage, the predicted service life of internal reinforcement with damage was substantially shortened, proving that, in a Cl\(^-\) environment, fatigue damage could significantly shorten the service life of concrete structures. Secondly, fatigue tests followed by wet and dry cycles also showed that the diffusion of Cl\(^-\) accelerated as the load increased. Wu [83] found that
the Cl\(^-\) content in concrete decreased continuously with the increase in the applied stress level, but the Cl\(^-\) content increased with increasing exposure age. As the study was further developed, domestic and foreign scholars conducted tests with the combined effect of wet and dry cycling, fatigue load, and Cl\(^-\) erosion.

It has been shown [53] that concrete under fatigue load has the highest reinforcement corrosion rate in the tidal zone, followed by reinforcement located in the submerged and atmospheric zones, and it was further found that reinforcement in concrete in the tidal zone is more sensitive to changes in stress ratios. Shen [84] found that, under the combined effect of fatigue load, wet and dry cycles, and Cl\(^-\) erosion, the cracking of the concrete’s protective layer was a slow process that develops from the inside out, with reinforcement corrosion causing cracks to develop from the inside towards the concrete surface; the fatigue load effect caused the pores to open and close periodically, allowing Cl\(^-\) to be adsorbed into the reinforcement on the side away from the protective layer. Pang [85] found that the residual yield load and ultimate load of beam specimens of RC decreased with increasing the maximum stress level of fatigue load after a cyclic load and 240 wet and dry cycles tests, and they concluded that the maximum stress level had an adverse effect on the yield load and ultimate load capacity, an effect that was greater than the effect of changing the number of cycles. Hua [86] simulated the actual working conditions of RC bridge structures in a coastal environment and undertook wet and dry cycles of seawater with a dry–wet ratio of 7:1 for 180 days at different stress levels and different numbers of fatigue cycles to determine the Cl\(^-\) content of concrete in the tension and compression zones. It was found that the Cl\(^-\) content in the tension and compression zones of fatigue-damaged RC beams was significantly higher than that of undamaged RC beams. When the stress level was \(\leq 0.3\), the chloride content of the concrete in the tension zone increased with the increase in the upper load limit; when the stress level was 0.4 times higher than the tensile strength and the number of fatigue loads was \(\leq 800,000\) times, the chloride content of the concrete in the tension zone increased with the increase in the number of fatigue loads. The chloride content of the concrete in the compression zone did not change significantly with the upper load limit, but it did increase with the increase in the number of fatigue loads. However, Wang [87] simulated the actual working conditions of concrete bridge structures in a coastal environment and chose a test similar to that found in the literature [86] and discovered that the Cl\(^-\) diffusion rate in the compression zone was higher than that in the tension zone for a fatigue stress level of 0.3 times higher than the tensile strength under the combined action of dry–wet cycles, fatigue load, and Cl\(^-\) erosion.

Figure 9 shows the variation in Cl\(^-\) content with depth for beams subjected to 800,000 fatigue cycles at different fatigue stress levels. Figure 10 shows the effect of the upper fatigue load limit on the diffusion coefficient at different measurement points, where B represents the beam. As observed in Figures 9 and 10, the Cl\(^-\) content in the tension zone, as reported in the literature [86], was significantly greater than the Cl\(^-\) content in concrete in the compression zone at a stress level of 0.3 times higher than the tensile strength, and it was seen that the Cl\(^-\) diffusion coefficient in the tension zone was greater than the Cl\(^-\) diffusion coefficient in the compression zone. The literature [87] showed that the Cl\(^-\) diffusion coefficient in the compression zone was distributed along the span of the beam at a stress level of 0.3 times higher than the tensile strength, which was significantly greater than that in the tensile zone. The tests in the literature [86,87] were similar, and the opposite conclusions were obtained, indicating that the internal changes in concrete under the combined effects of fatigue load, wet and dry cycles, and Cl\(^-\) erosion were complex, so they led to differences in the conclusions, and more relevant tests were needed to obtain conclusions regarding Cl\(^-\) transport in concrete under the combined effects of multiple factors.
The combination of multiple factors affects the durability of concrete, resulting in modeling that is often not comprehensive. Guan et al. [88] established a Cl$^-$ erosion model for concrete under fatigue load and dry–wet cycles based on the migration model of Cl$^-$ in dry–wet cycle environments, and they analyzed the influence law of different factors on Cl$^-$ migration in concrete through indoor tests. Wu [83] established a Cl$^-$ migration model considering diffusion, convection, and capillary modes; calculated the Cl$^-$ diffusion coefficient under fatigue load and dry–wet cycles; and obtained the relationship between Cl$^-$ diffusion coefficient and stress level. The results of the model analysis were basically consistent with the experimental results. Petcherdchoo [89], after proposing a model applicable to convection and diffusion, found that, at higher stress levels, the Cl$^-$ erosion rate would increase. The increase in the rate of Cl$^-$ accumulation on the concrete surface under dry–wet cycles at a stress level of 0.4 times higher than the flexural strength tends to the power of 2. Ma et al. [90] proposed a new model for predicting the fatigue damage of RC structures with dry–wet cycles. After integrating Cl$^-$ invasion, corrosion pit growth, concrete cracking, dry–wet cycles, and fatigue load, they proposed that rust expansion occurs after the corrosion of reinforcement. The load process produces the phenomenon of local stress concentration, and the local stress concentration leads to cracks as the time increases.

In the alternating test of multiple factors, it is often possible to study the changes that occur in one or two other factors under the action of multiple factors, which could play a certain reference role. It is not sufficient to study the actual effect of multiple factors acting together on the long-term durability of concrete. In the test of fatigue load, dry–wet cycles, and Cl$^-$ erosion acting together, it can be found that the rapid increase in the rate of Cl$^-$ erosion under the combined effect of fatigue load and dry–wet cycles accelerated the corrosion of reinforcement and eventually reduced the load-bearing capacity of concrete members. Extensive theoretical and practical studies are necessary to simulate
the prediction of the durability and lifespan of concrete under the combined impacts of fatigue load, wet-dry cycles, and Cl\(^-\) erosion.

5. Conclusions and Further Reflections

(1) Under the combined action of fatigue load and Cl\(^-\), the stress level and number of fatigue loads increased the transmission performance of Cl\(^-\) in concrete. Cl\(^-\) erosion leads to the reinforcement being more susceptible to rusting. The load-bearing capability of the RC under fatigue load was reduced after the corrosion of the reinforcement.

(2) The dry-wet cycles regime also affects the durability of concrete under the coupled action of dry-wet cycles and Cl\(^-\). Oxygen during the drying process also causes the corrosion of the reinforcement, which rusts and expands, leading to cracks in the protective layer of concrete and eventually causes structural damage.

(3) Studies on the combined effects of multiple factors tend to use alternating tests due to the large differences in test periods and the difficulty of achieving test conditions in the general laboratory. The alternating test mechanism used in existing studies cannot fully simulate the actual situations, resulting in final results that may differ significantly from real life.

(4) At this stage, there is little research on the available models. There are limitations and different ways of setting up these models, which make it difficult to achieve good uniformity.

In order to solve the problems we are currently facing in this field, the following is presented as a possible outlook to try to solve them. (1) The factors affecting the durability of concrete in the marine environment can be refined in future experimental studies, and multiple influencing factors can be tested in combination with each other in order to fit the real-life situation and solve the problems that may occur with concrete in practice. (2) It is the pore structure of the concrete that has the greatest influence on the performance of Cl\(^-\) transport, and it may be more appropriate to strengthen the study of the pore structure in the erosion pattern of Cl\(^-\) in concrete in order to establish a relevant model.

Author Contributions: Conceptualization, Z.L. and M.Z.; methodology, Z.L.; software, J.C.; validation, M.Z., Z.L. and J.C.; formal analysis, R.X.; investigation, Z.L.; resources, Z.L.; data curation, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, M.Z. and Z.L.; visualization, Z.L.; supervision, M.Z.; project administration, M.Z.; funding acquisition, M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China. No. (52078109).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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