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Investigation of Chloride Diffusion into Concrete with Joint

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The passive layer shielding the steel reinforcement from corrosion can be attacked by the chloride ions that permeate through the chloride ions that permeate through the pores in the concrete when it is in solution. This paper aims to explore the investigation of chloride diffusion into concrete with joint. Three exposure conditions were taken into consideration in chloride ion diffusion experiments in order to examine the impact of exposure conditions on the chloride ion diffusion property: long-term immersion in a static sodium chloride solution, long-term immersion in a circulating sodium chloride solution, and dry–wet cycles in a circulating sodium chloride solution. According to experimental findings, the age of erosion increased the chloride ion content at a particular depth. Furthermore, concrete subjected to dry-wet cycles of the circulating sodium chloride solution had slightly higher chloride ion content than concrete immersed in the solution for an extended period of time. Fick's second law served as the foundation for the empirical equations that were developed by fitting experimental data to determine the chloride content and diffusion coefficient at the concrete's surface, as well as the correlation coefficient values for various exposure scenarios. The calculation formula's greater applicability was confirmed by comparison with the experiment results. The chloride ion content could be predicted and examined using this method for various exposure scenarios.

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1. INTRODUCTION

Concrete cracks as a result of the stress brought on by volume changes, hence construction joints are built on purpose to ensure effective construction and crack control in mass concrete structures [1,2]. On the other hand, there are numerous engineering benefits which exist for concrete, including cost-benefit analysis, great durability, exceptional fire resistance, building efficiency, and a reliable supply chain [3,4]. However, due of its weak tensile strength, it permits cracks in the area that is under tensile stress. The tensile zone is where steel reinforcement is most frequently utilized, and it is made to withstand tensile stress [5,6]. According to some studies, the high alkali content and inadequate oxygen in concrete prevent steel from corrosion, but corrosion is easily caused when RC structures are exposed to a chloride environment. [7] “Due to a drastic drop in bonding strength and useful steel area, durability issues might develop into structural issues with corrosion” [8,9]. “In the previous study, the changing chloride diffusion behavior in cold joint concrete at the age of 91 days was evaluated considering various loading conditions and GGBFS effect, which revealed that the chloride diffusion coefficient increased regardless of loading types and addition of mineral admixture, if it had cold joint”. [10].

Construction joints are typically used for mass concrete structures, [11,12] such as RC columns for bridges and wall structures, to reduce cracking and ensure that concrete is placed efficiently within a certain amount of time [13,14]. “One of the key variables affecting concrete durability and shortening a building's lifespan is chloride diffusion. The composition of the concrete and its porosity are just two of the many variables that affect chloride diffusion” [15,16]. Since aggregates make up around 75% of the volume of common concrete mixtures, aggregate characteristics have a big impact on chloride dispersion and the resilience of concrete structures [17,18]. In order to estimate the service life of given buildings with known mixes and materials, multiple researchers by [19,20,21] have studied the problem of chloride diffusion and developed various chloride prediction and service life models. “A helpful foundation for constructing reinforced concrete structures in salt-contaminated settings has been created by” [22]. According research, adding silica fume (SF) and other materials that boost concrete's durability, [23] like fly ash (FA) and GGBS, at specific percentages can significantly improve concrete's durability [24]. “Quantitative data is needed to specify the boundary condition at the exposed surface, the effective chloride transport coefficient, and the corrosion initiation threshold level of chloride as specified by the applicable code in order for the model to function. A variety of experimental findings on the diffusion of acid-soluble chloride in various concrete mixtures have been presented by some studies” [25,26]. They have demonstrated that the length of time concrete is exposed to a chloride environment has a significant impact on the effective chloride transport coefficient. A mathematical model for chloride penetration in saturated concrete has been developed [27,28] taking into account the w/c ratio, cement type, aggregate content, curing time, temperature, and surface chloride iron concentration. “However, it has been noted that the main elements that affect concrete longevity are the near-surface concrete's permeability and the numerous transport systems that control chloride penetration” [29, 30]. For determining how long concrete would last, they performed tests on air permeability, freeze-thaw/salt scaling resistance, and an accelerated carbonation test. They came to the conclusion that a higher fraction of bigger aggregate reduces durability.

“In addition to, the effects of cement, water, curing conditions, and microsilica content on chloride diffusion characteristics were examined” [31,32]. They discovered that there is a relationship between w/c ratio and chloride diffusion, and that this relationship varies depending on the different microsilica compositions. They came to the conclusion that the influence of high w/c ratios on chloride ingress is significantly more noticeable in mixes with low microsilica content and that cement content has no effect on chloride ingress in mixes with high microsilica content [33]. Additionally, they found that when the w/c ratio of the mixes is held constant, the influence of microsilica content on the diffusion coefficient, Dc, is less pronounced. A series of studies have investigated the carbonation of concrete subjected to a hot, arid climate like that of the United Arab Emirates [34,35,36]. Their findings demonstrated that the usage of surface coating, the water/cement ratio, the water-curing time, and the season in which the concrete was initially cast and exposed were the most important variables influencing concrete carbonation. They also came to the conclusion that a lower water/cement ratio and a longer water-curing time led to less carbonation in concrete.

"It is clear that research on concrete durability has captured the interest of several scientists across the globe, including those in the Arabian Gulf. Without sufficient research on the effects of chloride exposure, the usage of concrete has expanded in the UAE, which is a significant long-term concern for this region" [37,38]. When employing local materials in the harsh environment of the UAE, where the building sector is growing at an unprecedented rate, the authors believe that this study is crucial for this region. This study is the first stage in an ambitious plan to investigate the chloride diffusion into concrete with joint in various parts of the globe considering the difference environmental and climatic conditions.

"Furthermore, the effectiveness of chloride diffusion under prolonged load has been covered in some research. According to studies, the diffusion of chloride ions will not always be hampered by an increase in sustained compressive stress" [39,40]. "The experimental findings demonstrate that when the sustained compressive stress is greater than $0.3f_c$ (for example, f_c = prism compressive strength at 28 days), the chloride diffusion coefficient increases" [41,42]. "However, biaxial sustained stress will also have an impact on the diffusion of chloride ions in concrete" [43,44,45]. "By employing additive concrete under biaxial sustained pressure stress, Xingcai Wei investigated the permeability of chloride ions and discovered that this process is not always inhibited by an increase in compressive stress. In the experiments mentioned above, the link between stress level and chloride content of concrete with various w/c (i.e., water/cement) ratios was not thoroughly explored. The chloride diffusion characteristics of several types of w/c concrete under biaxial sustained compressive stress are rarely studied. The diffusion of chloride in concrete structures with various w/c ratios under biaxial sustained compressive stress must therefore be studied.The purpose of this study is to examine the diffusion law of chloride ions in concrete under various compressive stress circumstances in light of the brief discussion that has gone before. In this study, concrete is subjected to a number of chloride ion penetration tests under uniaxial and biaxial sustained compressive stress, and the variation law of chloride concentration in concrete is examined. The apparent chloride diffusion coefficient under stress condition is then calculated using Fick's second law diffusion equation, and its variation under prolonged uniaxial and biaxial compressive stress is examined. The models for chloride diffusion under various stress situations are developed. The experimental evidence from the published literatures confirms the applicability of the diffusion models" [46-52].

2. FICK'S 2nd LAW

"Generally, diffusion of ions through porous media are assumed to follow Fick's 2nd law, $\frac{\partial C}{\partial t} + \nabla J = 0$ where J, *C*, and *t* are the flux, ion concentration, and time, respectively. Chloride can be found in concrete either physically or chemically bound to the cement paste matrix or as free chloride in the pore solution. In case of a chloride concentration gradient, a chemical potential gradient drives free chloride ions toward lower chloride concentration areas. However, due to lower mobility of positively charged cations compared to chloride ions, a "counter-electrical field" will also slowdown the movement" [46]. "The flux of chloride species is then considered to follow the Nernst-Plank equation $J = -D\nabla C\,(1 + \nabla \text{In}\, y) - DC\,\frac{XF}{RT}\nabla\Psi$ where *D*, *γ*, *z*, *F*, *R*, *T*, and *Ψ* are diffusion coefficient, chemical activity coefficient, valence of ions, Faraday constant, universal gas constant, absolute temperature, and counter-electrical potential, respectively. The chemical activity and counter-electrical potential terms depend on the concentration of free chloride as well as the ionic composition of the concrete pore solution" [46].

2.1 A Test-Based Program

2.1.1 Preparation of materials and specimens

The following materials were needed to make concrete. Three categories—categories D, categories E, and categories F—were used to group concrete specimens. To evaluate the effects of uniaxial sustained and biaxial sustained compressive loads on chloride intrusion, respectively, Categories D and E were used. Non-loading was applied to Category F. Portland cement supplied by Changsha and meeting GB 175-2007 standards had a characteristic compressive strength of 42.5 MPa. Table 1 illustrates the cement's chemical makeup. As coarse aggregate, gravel with a maximum size of 20 mm and a density of 1550 kg/m3 that is accessible in Liu yang City, Hunan Province, China is used. The fine aggregate used was naturally occurring river sand, with a fineness modulus of 2.3 to 3.1. Poly carboxylic ethers superplasticizer (SP), created by Shandong Huawei Yinkai Building Materials Science and Technology Co., Ltd., was applied to all concrete sample. In Table 2, the concrete mix ratio is displayed. Following their creation, these specimens were cured for 28 days in a curing room at a temperature of 20 2 °C and a relative humidity of 90 5%. When the compressive strength of several concrete specimens was tested, the measured values were 47.21 MPa, 52.68 MPa, and 56.78 MPa, respectively, for concrete with w/c ratios of 0.44, 0.40, and 0.36. In the chloride diffusion experiment, the remaining concrete specimens were continuously compressed.

2.1.2 Test and experimental arrangements

For proper analysis, the one-dimensional diffusion law of chloride in concrete under sustained pressure stress [46,47] we coated the other five surfaces of the specimens with epoxy resin apart from the penetration surface. “To lessen the impact of the concrete boundary on the chloride diffusion process, the 100 mm central area of the concrete specimen's upper surface was chosen as the chloride ions penetration surface, and the upper surface was treated with wear reduction before the concrete specimens with various w/c ratios were put into the loading device for the loading test” [52]. The concrete specimen's long and short sides' stresses were denoted by the letters cx and cy, respectively. The concrete specimens are arranged neatly in the axial direction of the loading device for categories D (one-dimensional loading), and the compressive stress was tracked and managed by the screw jack's pressure measurements, as illustrated in Fig.1. Each concrete specimen for categories E (two-dimensional loading) is equipped with a force transfer plate on the lateral side, as illustrated in Fig. 2, with the exception that the axial direction is consistent with that of categories D. On the force transfer plate is a compressive ring that is the same size as the side length of the concrete specimen. The pressure ring was put on one side of the loading plate, and the screw jack was in contact with the other. The numerical values of the three pressure rings were equal and reached the stress design value after adjusting the screw jack to manage the pressure rings' numerical values. Researchers have discovered that the characteristics of concrete materials change significantly when the biaxial compressive stress ratio is between 1:1 and 1:25. Concrete specimens in Category F, the control group, were not stressed. The parameters Fd0, Fe0, and Ff0, respectively, were used to represent the concrete with w/c ratios of 0.44, 0.4, and 0.36. In the same loading apparatus, concrete specimens received the same amount of compressive stress.

2.1.3 Experiment with diffusion and measurement of chloride concentration

The prefabricated chloride trough was positioned on the concrete permeable surface and bonded to the concrete sample by the adhesive after the compressive stress was stabilized. With the aid of a beaker, the 3.5% NaCl solution was inverted in the chloride trough. The temperature of the artificial climate simulation box where the chloride ions penetration experiment was conducted was set between 20 and 22 °C. Concrete samples were exposed to chlorine salt for two months. To prevent precipitation and maintain a consistent chloride concentration, the solution in the chlorine salt trough was changed every week [48]. Following that, concrete specimens must be sampled in accordance with JTS/T 236-2019 standard. Vertical to the concrete-permeated surface was the drilling rig. Six measuring locations with distances of 0–5 mm, 5–10 mm, 10-15 mm, 20–25 mm, and 25–30 mm from the penetrated surface were produced by boring holes inward to collect powder. Three data points for the drilling depth of the same stratum were collected to reduce the impact of mistakes. The powders were dried in an oven at 105 °C for two hours, and then they were cooled to room temperature in a desiccator. Following that, a sample of concrete powder was tested for chloride concentration in accordance with JTS/T 236-2019 standards.

Table 1. Chemical composition of cement

Ingredients	SiO_2	Al_2O_3	CaO	MgO	SO_2	Loss on ignition
Mass percent (%)	21.53	5.55	62.29	3.52	3.17	1.78

Table 2. Mix ratio of concrete test block

Unit Content (kg/m³)						
Type	**w/c**	**Water**	**Cement**	**Fine Aggregate**	**Coarse Aggregate**	**SP**
C45	O.45	181	408.07	542.26	1267.65	3.39
C50	0.40	181	450.00	531.00	1239.10	3.14
C54	0.36	181	500.00	516.00	1204.00	3

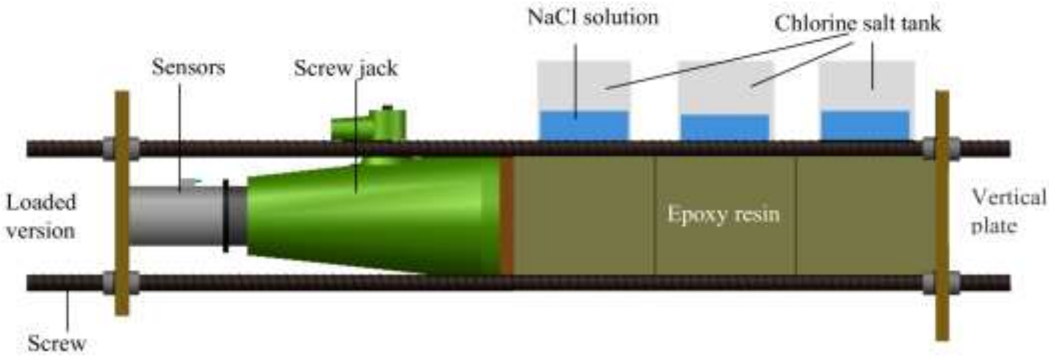

Fig. 1. Uniaxial loading

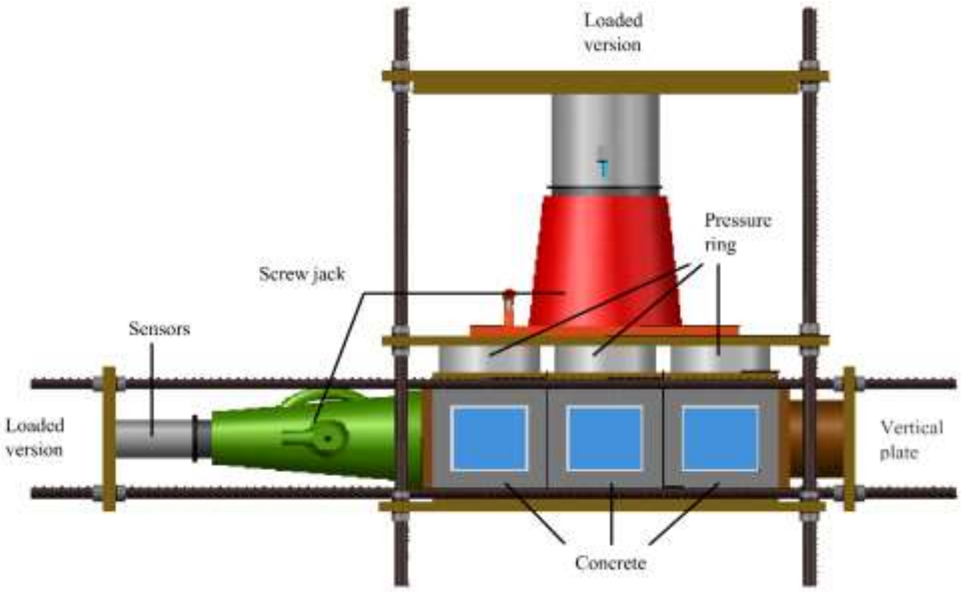

Fig. 2. Biaxial loading

2.2 Test Findings and Analysis

2.2.1 Chloride concentration distribution under various axial compressive stresses

Fig. 3 displays the distributions of chloride in the concrete specimens under uniaxial sustained compressive stress (categories D) and zero stress (categories F). Consider the numbers for the chloride concentration at a depth of 7.5 mm. As shown in Fig. 3a, the chloride concentration values of the DCd1, DCd2, DCd3, and DCd4 specimens are, respectively, 21.05%, 34.58%, 29.41%, and 10.85% less than those of the Fd0 specimens in the same stratum. Fig. 3b demonstrates that the chloride concentrations of the DCe1, DCe2, DCe3, and DCe4 specimens in the same stratum are 16.83%, 33.75%, 27.84%, and 6.92% lower than those of the Fe0 specimens. As shown in Fig. 3c, the chloride concentration values of the DCf1, DCf2, DCf3, and DCf4 specimens are lower than those of the Ff0 specimens in the same stratum by 14.23%, 28.93%, 23.43%, and 4.90%, respectively. According to Fig. 3, when compared to Fd0, Fe0, and Ff0 specimens, the average chloride concentration values of DCd2, DCe2, and DCf2 specimens are, respectively, reduced by 35.04%, 30.21%, and 22.23%. With an increase in sustained compressive stress, the chloride concentration values of DCd3, DCe3, and DCf3 specimens are, on average, 1.20 times, 1.17 times, and 1.13 times higher than those of DCd2, DCe2, and DCf2 specimens. Similar to how DCd4, DCe4, and DCf4 specimens have much greater chloride concentrations than DCd3, DCe3, and DCf3 specimens. According to the results of the aforementioned tests, concrete with a high w/c ratio was more vulnerable to external prolonged compressive stress, and C45 concretes performed better in diffusing chloride than C55 concretes did. Concrete sample' chloride concentration drops and their ability to diffuse chloride ions is hampered when the applied sustained compressive stress is less than or equal to 0.3 fc. Concrete sample' chloride ion diffusion would be encouraged if a sustained compressive stress larger than 0.3 fc was applied.

Depths of 12.5 mm and 22.5 mm in concrete. Fig. 4a shows that as the stress level rises, the chloride content in concrete initially declines somewhat before rising quickly. The chloride concentration in concrete with various water/cement ratios drops when values of 1 are close to 0.3. As seen in Fig. 4b, the chloride content of concrete is unaltered. when 1 is less than or equal to 0.3, the impact of compressive force on chloride concentration at great depths. When 1 is more than 0.3, as seen in Fig. 4a, b, the chloride concentration in concrete rises. The chloride concentration of the C45 concrete specimen is higher than that of the C55 concrete specimen under the same prolonged compressive stress.

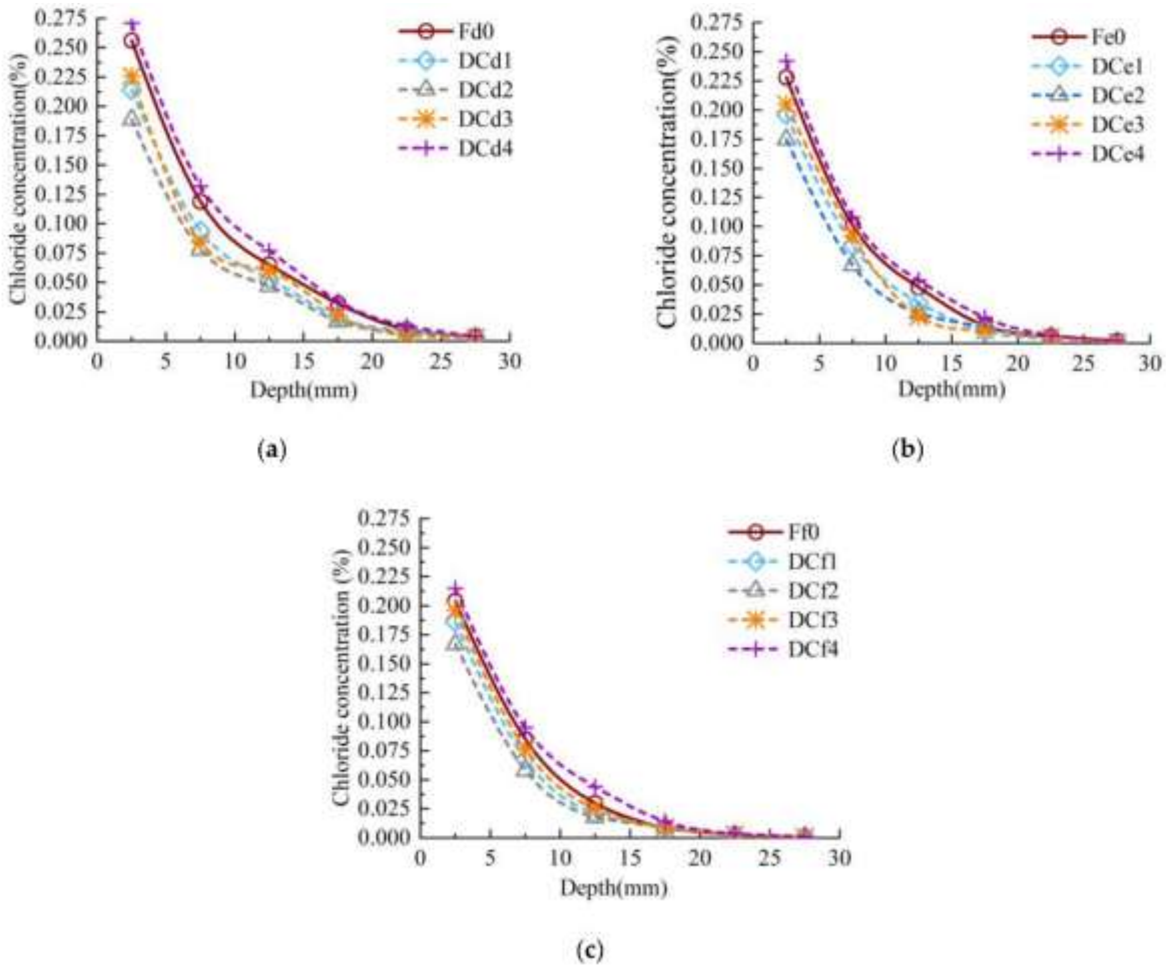

Fig. 3. Chloride concentration distribution of concrete with three *w/c* ratios under uniaxial sustained stress: (a) *w/c* = 0.44; (b) *w/c* = 0.4; (c) *w/c* = 0.36

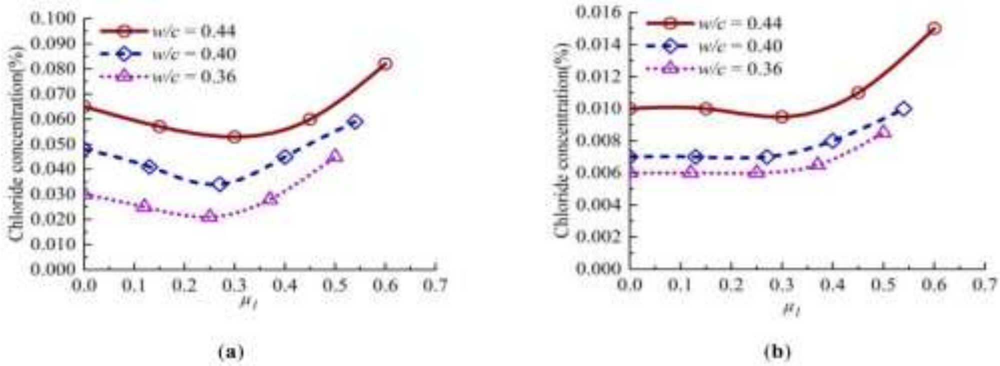

Fig. 4. Depicts the variations in chloride concentration with stress level 1 at diffusion

3. CONCLUSION AND REMARKS

3.1 Conclusion

After conducting systematic experiments and numerical investigations, it was discovered that, the age of erosion increased the chloride ion content at a particular depth. Furthermore, concrete subjected to dry-wet cycles of the circulating sodium chloride solution had slightly higher chloride ion content than concrete immersed in the solution for an extended period of time. Transverse cracks impact the migration of chloride ions. Crack widths smaller than 0.15 mm impose little influence on chloride ions transmission due to the self-healing effect inside the cracks. For crack widths of 0.15 mm and 0.20 mm, the chloride ion migration coefficient increased by one to two orders of magnitude and steel corrosion is accelerated. However, for crack widths exceeding 0.20 mm, this effect gradually weakened. The effect range of transverse cracks on chloride ion transport is ~20 mm. The chloride migration coefficient 20–50 mm from the cracks is similar to that of more than 50 mm from cracks. Transverse cracks affect the steel corrosion process by accelerating the corrosion rate of steel bars and increasing the corrosion production distribution area. Wider crack leads to a faster corrosion rate. The corrosion rate and corrosion production distribution area in concrete with crack of 0.30 mm is almost four times as much as that in concretes with 0.15 mm. CR steels can be used in reinforced concrete structures in marine environments because the corrosion-resistance of CR steel is superior to that of LC steels due to the naturally forming passive film in low alloy steels.

3.2 Remarks

The results of the experiment lead to the following deductions.

1. The transport of chloride ions from the environment into concrete is altered by the presence of continuous compressive stress. It is discovered that concrete specimens under axial sustained compressive stress of 0.3 fc have a maximum chloride content that is approximately 35% lower than those under no stress. The greatest chlorine content in the concretes with the axial and lateral sustained compressive stress of 0.3 fc and 0.15 fc is decreased by approximately 50% in comparison to those without stress. In addition, when the sustained compressive stress is more than 0.3fc, the diffusion process and concentration of chloride ions will increase. When the lateral sustained compressive stress is greater than 0.15 fc in biaxial concrete, the chloride concentration distribution is 1.27–1.1 times that of the lateral sustained compressive stress. The diffusion of chloride ions will be further improved as the level of prolonged compressive stress rises.
2. The chloride content of C45 concrete specimens is higher than that of C54 concrete specimens under the same sustained compressive stress. This is done because a higher w/c ratio results in inferior quality concrete, which makes the structure less dense and more sensitive to the effects of long-term compressive stress. As a result, concrete samples with higher w/c ratios had greater permeability. The created chloride diffusion coefficient model takes into account the impact of concrete's sustained uniaxial and biaxial compressive stress. The model is useful for estimating how long concrete constructions will last in environments with a lot of chlorine.
3. It is advised that future study measure concrete cracks under continuous stress conditions throughout the experiment. the

fracture depth and concrete's pore size distribution under sustained load in order to potentially expand and enhance the model.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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