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Effect of Repeated Loading on the Flexural Load Carrying Capacity of Marine Concrete Beams Exposed to Chloride Environment

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Abstract. *To investigate the effect of repeated loading on the flexural load carrying capacity of marine concrete beams suffering from chloride attack, a total of 10 marine concrete beams and 27 concrete cubes were designed for flexural performance test and compressive strength test, respectively. Three damage mechanisms, including repeated loading with a stress level of 0.4, chloride salt dry-wet cycles and coupling action of repeated loading history and chloride salt dry-wet cycles, were applied for concrete beams and cubes. Test results show that the effect of repeated loading on the degradation of compressive strength of concrete is significantly higher than that on the flexural properties of concrete beams, and the corresponding degradation ratio between them is maintained at about 1.5. The effect of chloride salt dry-wet cycles on concrete compressive strength is 1.8 times higher than that on the flexural load carrying capacity of test beams. Combined with the test data proposed in this paper and some existing studies, the influence of compressive strength loss on the flexural load carrying capacity of marine concrete beams was discussed. The analysis shows that the compressive strength loss rate can effectively reflect the remaining flexural load carrying capacity of marine concrete beams and there is an exponential relationship between them.*

Keywords: *Repeated Loading, Chloride Salt Dry-wet Cycle, Marine Concrete Beam, Compressive Strength, Flexural Load Carrying Capacity.*

1 Introduction

In coastal areas, reinforced concrete structures are not only subjected to chloride ion attack but also to various external loads during their service life (Lu 2018). Under the action of chloride attack and external load, the expansion of cracks in reinforced concrete beams accelerates and the corrosion of internal reinforcement increases, resulting in the accelerated degradation of the beam's flexural load carrying capacity, which seriously affects the durability of these structures (Dong et al. 2017, He et al. 2020).

In recent years, researchers have carried out some experimental research and theoretical analysis on the performance degradation of concrete elements under chloride salt attack and external load. The application of load usually accelerates the formation and expansion of concrete cracks (Zhao et al. 2019), but the expansion and distribution of cracks are greatly restrained by the hoop reinforcement(Zhao et al. 2021, Xu et al. 2021). The bond between concrete and steel bar degrades progressively with the reinforcement corrosion and the application of external load (Fang et al. 2006, Zhou et al. 2015, Shang et al. 2021). The reductions in flexural stiffness and load carrying capacity should be more pronounced in concrete beams subjected to a combination action of chloride attack and loading than those in beams subjected to a single factor (Liu et al. 2016, Li et al. 2018).

Most of the above studies have focused on the property degradations of concrete members only under external loads or chloride salt dry-wet cycles, without considering the coupled attack of load and chloride ions. Therefore, in this study, three damage mechanisms (repeated loading with stress level of 0.4, chloride salt dry-wet cycles and coupling action of repeated loading history and chloride salt dry-wet cycles) were designed in this paper to conduct compressive strength tests and flexural performance tests on marine concrete blocks and test beams，to investigate the effect of compressive strength loss rate on the residual flexural load carrying capacity of marine high performance concrete beams exposed to chloride environment and repeated loading in detail.

2. Test Method

2.1 Specimens

The concrete proportions are shown in Table 1. P.O 42.5 ordinary Portland cement, Class II fly ash and S95 slag were used as cementitious material. Crushed stone in size of 5~25mm was used as coarse aggregate and river sand with a fineness modulus of 2.4 was used as fine aggregate.

Table 1. Concrete mix ratio(kg/m^3)

Cement	Fly ash	Slag	Water	Fine aggregate	Coarse aggregate	Water reducing agent
200	80	120	160	700	1140	0.8

In order to investigate the concrete compressive strength changes on the flexural load carrying capacity of the marine concrete beam, the test beam and 100mm×100mm×100mm concrete test blocks (3 per group) were poured at the same time. A total of 10 groups of marine concrete beams with concrete test blocks were designed. The specific structure of concrete beam is shown in Fig 1. The damage working conditions and parameters of the test pieces are shown in Table 2.

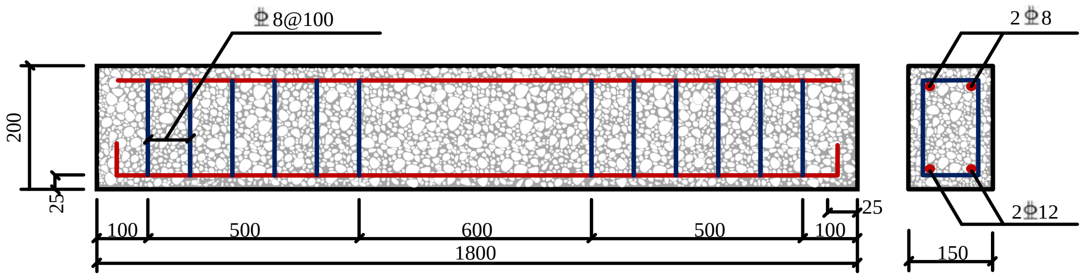


Figure 1. Detail of marine concrete beams construction (Unit: mm).

2.2 Application of Repeated Loading and Chloride Salt Dry-wet Cycle

Firstly, a repeated load of 0.4 M_u was applied to the test beam numbered ②③⑥⑦⑧⑨(M_u was measured by the test beam and its ultimate bending moment was 22.24kN • m). The load was held for 10 minutes after loading to the target value, then unloaded to 0 and left for 10 minutes before continuing to load until the design has been loaded multiple times. Simultaneously apply the same load level (taken as 0.4) and the same number of repeated loading to the concrete blocks ②③⑥⑦⑧⑨.

The test beams and test blocks numbered ④ to ⑨ were placed into 5% Nacl solution for chlorine erosion test. The method of chloride salt dry-wet cycles is shown in Fig 3. Each cycle lasted 7 days and the ratio of dry-wet was 4:3. After the chlorine salt erosion of the last batch of test beams and test blocks was finished, the compressive strength of all test blocks and the flexural load carrying capacity of the test beams were measured.

Table 2. Damage conditions and parameters of concrete test blocks and test beams

Working conditions	Specimens			Number of repeated loading	Number of chloride salt dry-wet cycle
	No.	Test beams	Test blocks		
Control group		B	-	-	-
	①	B-0-0	C-0-0	-	-
Repeated loading	②	B-10-0	C-10-0	10	-
	③	B-30-0	C-30-0	30	-
Chloride salt dry-wet cycle	④	B-0-20	C-0-20	-	20
	⑤	B-0-40	C-0-40	-	40
Coupling effect	⑥	B-10-20	C-10-20	10	20
	⑦	B-30-20	C-30-20	30	20
	⑧	B-10-40	C-10-40	10	40
	⑨	B-30-40	C-30-40	30	40

Note: Test beam "B" in the control group tested for ultimate bending moment after 84 days of maintenance; The sequence of coupling effect was repeated loading, followed by chloride salt dry-wet cycles;

Figure 2. Diagram of repeated loading.

Figure 3. Diagram of chloride salt dry-wet cycle.

3 Test Results and Analysis

3.1 Compressive Strength Loss of Test Blocks

3.1.1 Repeated loading

The change of compressive strength of concrete blocks is shown in Fig. 4. With the increase of number of repeated loading, the compressive strength of concrete decrease rapidly and tend to be stable. The specific performance is that the compressive strength of concrete blocks decreased by 2.69% after 10 times of repeated loading and 5.03% after 30 times, respectively. This is because the internal pores of the concrete expand faster at the beginning of loading. With the increase of the number of repeated loading, the internal pores development gradually tend to stabilise (Ye et al. 2012).

3.1.2 Chloride salt dry-wet cycle

At the beginning of the chloride salt dry-wet cecles, the compressive strength shows a large increase trend. At the 20th time of chloride salt dry-wet cycle, the compressive strength increased by 13.11%. At the later stage of chloride salt dry-wet cycles, the excess hydration products inside the concrete and the swelling damage produced by salt crystallization led to the reduction of the concrete strength. But the overall strength was still higher than the initial strength. At the 40th time of chloride salt dry-wet cycle, the compressive strength increased by 10.24%.

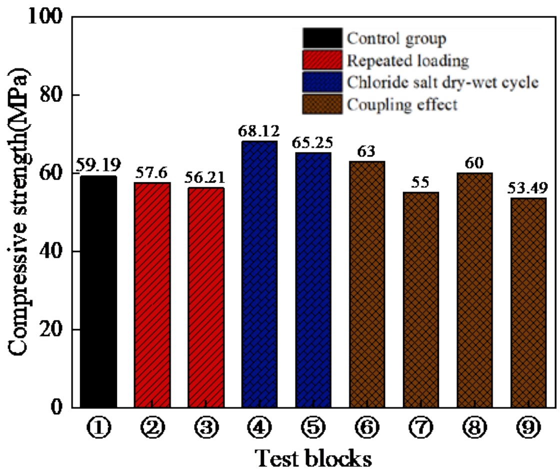


Figure 4. Compressive strength diagram of concrete test blocks.

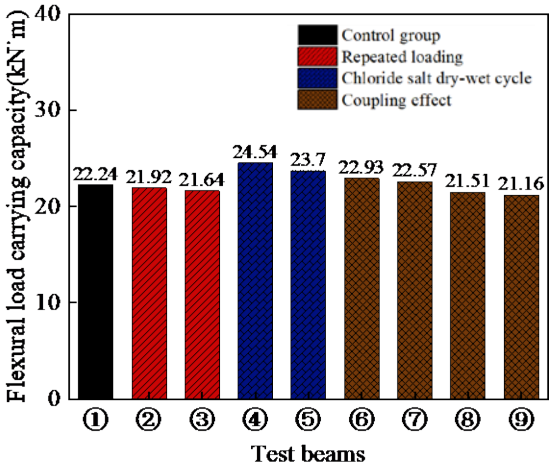


Figure 5. Flexural load carrying capacity diagram of test beams.

3.1.3 Coupling effect

Under the coupling effect, the compressive strength of concrete block tends to increase and then deteriorate as the time of chloride salt dry-wet cycles increases. After 20 times of chloride salt dry-wet cycles, the compressive strength of concrete blocks was improved after repeated loading. However, the compressive strength of concrete blocks lower than that of concrete blocks which did not experience repeated loading. This may be due to the fact that the repeated loading caused damage to the interior of the concrete specimens and further expansion of the existing cracks. Therefore, the hydration products of the mineral admixtures first filled such cracks and subsequently repaired the existing pores. This is because the more times the concrete specimen is loaded under load, the more serious its internal cracks expand, more conducive to the intrusion of chloride ions into the concrete interior (Yin et al. 2017). Also, a large number of reactants and the formation of salt crystals cause excessive expansion of internal stresses, thus increasing its deterioration.

3.2.Analysis of Test Blocks Compressive Strength Loss on Bending Load Capacity Degradation of Test Beams

3.2.1 Analysis of compressive strength of test block and degradation of flexural load carrying capacity of test beam under repeated loading

Fig 6 shows the fitting of the rate of loss of compressive strength of test blocks and the degradation of flexural load carrying capacity of test beams under repeated loading. From the figure, it can be seen that with the increase of repeated loading, the loss of compressive strength of test blocks and the degradation of flexural load carrying capacity of test beams gradually tends to stabilize from increasing. The ratios of the degradation rates at 10 and 30 repeated loading actions were 1.82 and 1.86, respectively. Under the action of repeated loading, the loss of compressive strength of concrete and the degradation of flexural load carrying capacity of concrete have a very high correlation.

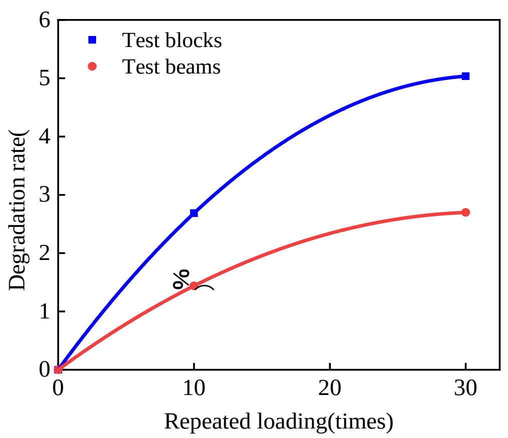


Figure 6. Effect of repeated loading on degradation.

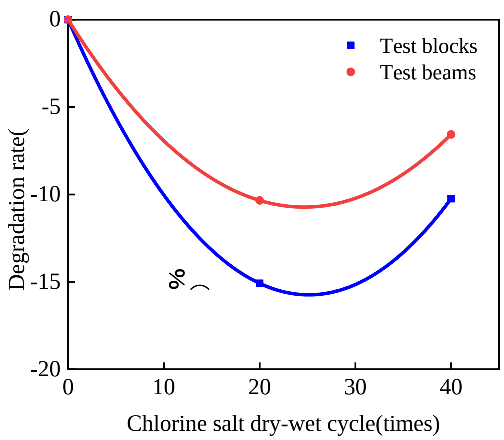


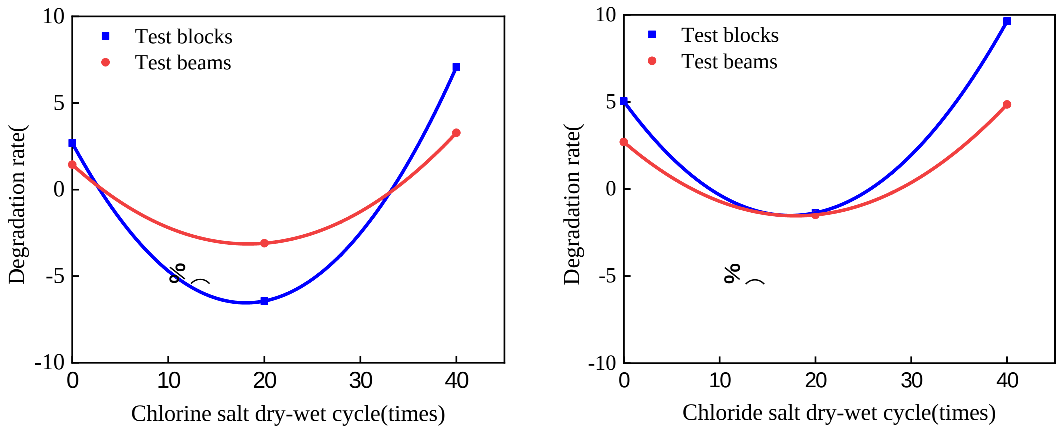
Figure 7. Effect of chloride salt dry-wet cycles on degradation.

3.2.2 Analysis of compressive strength of test blocks and degradation of flexural load carrying capacity of test beams under the action of chloride salt dry-wet cycle

Fig 7 shows the fitting of the rate of loss of compressive strength of the test blocks and the degradation of flexural load carrying capacity of the mixed test beams under the action of chloride salt dry-wet cycles. It can be seen from the figure that the test blocks and test beams have some improvement in compressive strength and flexural load carrying capacity because of the hydration under the short-term chloride salt dry-wet cycles. The degradation rate ratio of both is 1.46 at 20 times of chloride salt dry- wet cycles and 1.56 at 40 times of chloride salt dry-wet cycles. There is a high correlation between the loss of compressive strength of concrete and the degradation of flexural load carrying capacity of beams under chloride salt attack.

3.2.3 Analysis of compressive strength of test blocks and degradation of flexural load carrying capacity of test beams under repeated loading history coupled with chloride salt dry-wet cycle

Fig 8 shows the fitting of the rate of loss of compressive strength of the test blocks to the degradation of the flexural load carrying capacity of the test beams under repeated loading history and chloride salt dry-wet cycles. For the concrete test blocks, at 10 repeated loading, as the number of chloride salt dry-wet cycles increases, there is a greater degradation in compressive strength of the concrete test blocks than the increase in flexural load carrying capacity of the concrete test beams. For the concrete test beams, the same rate of degradation of compressive strength and flexural load carrying capacity occurred several times with increasing numbers of repeated loading and chloride salt dry-wet cycles. The graph shows that there is also a close relationship between the rate of loss of compressive strength and flexural load carrying capacity under the coupled effect of repeated loading history and chloride salt environment.



(a) After 10 times of repeated loading. (b) After 30 times of repeated loading.

Figure 8. Effect of chloride salt dry-wet cycles of degradation of concrete specimens after suffering from different times of repeated loading.

3.2.4 Model building and model validation

Collecting this paper and existing literatures, the data of compressive strength loss and corresponding residual flexural load carrying capacity of concrete in the compressive zone of marine concrete beams were counted. The compressive strength loss and corresponding residual flexural load carrying capacity were fitted, as in Fig 9, and the following equations were obtained:

$$R_M = 1.00228e^{-0.00465\lambda_f} \qquad R^2 = 0.9065 \qquad (1)$$

where R_M is the ratio of the bending capacity of the damaged beam to the flexural load carrying capacity of the intact beam, λ_f is the ratio of the compressive strength loss value of the beam concrete to the initial value.

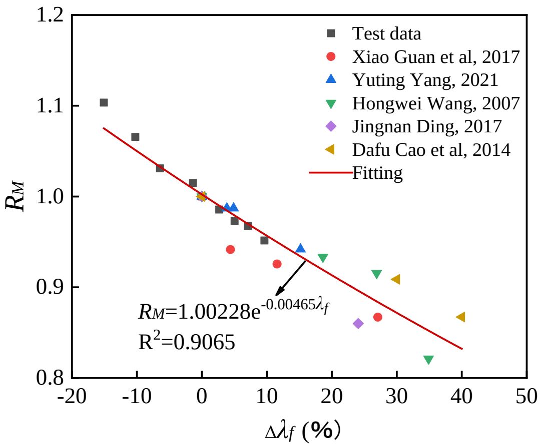


Figure 9. Influence of compressive strength loss on flexural load carrying of concrete beams.

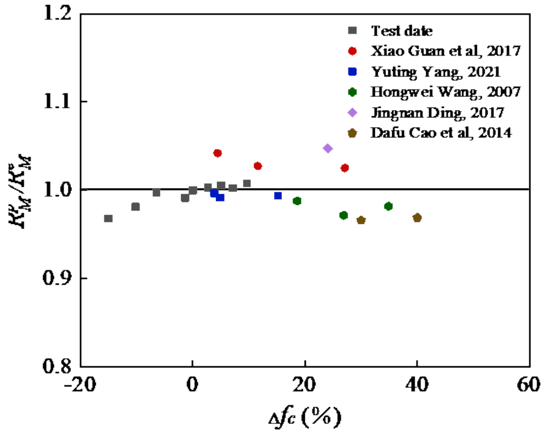


Figure 10. Ratio of predicted and calculated residual flexural load carryring capacity rate.

Combining the test results of this paper with those of the existing literatures, the calculation model proposed in the paper was used to calculate the residual flexural load carrying capacity of the test beams in the above literature. Also, the ratio of the corresponding predicted value R_M^p to the experimental value R_M^e is summarised in Fig 10. The ratio of R_M^p/R_M^e is basically in the range of 0.97 to 1.04, with a mean value of 0.9979 and a coefficient of variation of 2.2294%. The above results show that the calculation model given in this paper has good prediction results in terms of compressive strength loss to measure the remaining flexural load carrying capacity of marine concrete beams and the relevant model is feasible.

4 Conclusions

- Under repeated loading, the compressive strength of the marine concrete blocks and the flexural load carrying capacity of the test beams decreased rapidly and gradually stabilized. Also, the effect of repeated loading on the compressive strength of concrete was significantly higher than that on the flexural load carrying capacity of the concrete beams.
- The compressive strength of the concrete blocks and the flexural load carrying capacity of the concrete beams both increased in the short term due to the development of hydration under the chloride salt dry-wet cycles. Also, the increase in the compressive strength of the test blocks was significantly higher than that in the flexural load carrying capacity of the concrete beams.
- Based on this paper and the existing literature data, a model for calculating the residual flexural load carrying capacity of marine concrete beams is proposed. It is proved that when the loss rate of compressive strength is less than 40%, the residual flexural load carrying capacity of marine concrete beam can be effectively measured by using the model of this paper.

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