Chloride ion Erosion of Cracked Concrete under Load

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Abstract. In order to study the effect of load on chloride ion erosion before cracking, cracking critical state and instability failure state, three-point bending beam fracture test was carried out. The specimens were loaded at three loading levels: pre-crack load, crack load and peak load, then chloride ion content in the cracked section of the concrete was measured by borehole sampling method after immersion in 8% sodium chloride solution for 30, 60, 90 days. The test results show that at the same depth of cracking section, the content of chlorine ion increases with the load level. The chloride ion content with wedge erosion is significantly higher than that without wedge erosion under the same conditions and the increasing trend of chloride ion content under peak load is more significant. The chloride diffusion coefficient decreases with erosion time when the load is less than the initiation load, and chloride ion diffusion coefficient increases slowly with erosion time when load is greater than the initiation load. The stress intensity factor of concrete is positively correlated with chloride ion diffusion coefficient.

1. Introduction
Chloride erosion is the most serious and common reason for durability failure of concrete structures. In practical projects, most concrete works with cracks. Generation and development of cracks would change the permeability of concrete and have an adverse impact on concrete structures. Therefore, chloride ion erosion of cracked concrete should not be neglected.

In recent years, chloride ion erosion of cracked concrete was studied by many researchers. Ismail[1] worked out an experimental study on chloride ion diffusion in cracked mortar specimens. Influence of crack width on chloride ion diffusion characteristics of concrete was studied by Djerbi[3] and Jang[4]. Moreover, the concept of ‘threshold crack width’ is proposed and considered to be around 80µm, when crack width is greater than 80µm, and the diffusion coefficient does not increase with the increase of the crack width. On this basis, Bentz[5] studied the influence of fracture density on chloride ion diffusion. In addition, many scholars have done a lot of research in numerical simulation. Kamali[6] used graphical method to predict the effect of cracks on chloride ion diffusion. Chloride ion diffusivity in fractured and intact mortar is calculated by chloride ion diffusivity modeling under one-dimensional tensile load and different strains [7]. Many scholars have studied chloride ion erosion under load. Influence of compression load on chloride ion diffusion coefficient of concrete is the most common [8-9]. Influence of bending load on chloride diffusion in concrete was also studied [10-11].

At present, researches on chloride ion erosion in the process of concrete fracture, especially in the critical state of cracking under load are still not enough. This paper discusses load effecting on chloride ion erosion of cracked concrete in three stages: before crack initiation, crack initiation and crack failure. It provides a reference for the study of chloride ion erosion in the critical cracking state.
2. Experimental programs

2.1 Specimen preparation
Concrete mix ratio and 28d compressive strength were shown in table 1. The concrete specimen used in the test was shown in figure 1. The water-cement ratio was 0.49.

| Sample | Water/(kg/m³) | Cement/(kg/m³) | Fly ash/(kg/m³) | Sand/(kg/m³) | Coarse aggregates/(kg/m³) | 28d compressive strength/MPa |
|--------|---------------|----------------|-----------------|--------------|---------------------------|-----------------------------|
| C30    | 220           | 381            | 68              | 606          | 1125                      | 34.8                        |

Table 1. Mixing proportion of concrete

![Figure 1. Schematic diagram of specimen](image)

2.2 Concrete loading test
Load test was carried out on concrete specimens. The parameters were divided into 7 groups which are shown in table 2. The groups were as follows: not loaded (Group1); the loading stopped and wedge was immediately inserted in the crack of prefabricated specimen when loaded to 2kN (Group2, Group3); the loading stopped and wedge was inserted when loaded to cracking load (Group4, Group5); the loading stopped and wedge was inserted when loaded to peak load (Group6, Group7).

| Group | Sample No. | Load value/kN | Insert wedge | Cracks appear |
|-------|------------|---------------|--------------|---------------|
| 1     | 0-D30,60,90| 0             | ×            | ×             |
| 2     | S-2kN-D30,60,90 | 2       | ×            | ×             |
| 3     | C-2kN-D30,60,90 | 2       | √            | ×             |
| 4     | S-CL-D30,60,90 | F_{\text{ini}} | ×            | ×             |
| 5     | C-CL-D30,60,90 | F_{\text{ini}} | √            | ×             |
| 6     | S-PL-D30,60,90 | P_{\text{max}} | ×            | √             |
| 7     | C-PL-D30,60,90 | P_{\text{max}} | √            | √             |

Table 2. Sample parameters

Before concrete loading test, three-point bending beam fracture test was carried out in order to calculate crack initiation load and peak load. Crack initiation load was concentrated in the range of 2.85kN-3.15kN, so 2kN is selected as the unified representative load value to study before concrete cracking. Cracking concrete loading test device was shown in figure 2.

![Figure 2. Concrete loading test](image)

The purpose of inserting wedge is to keep concrete porosity around crack closing to the loading condition until wedge is removed from precast crack. The wedge should be quickly inserted into the prefabricated crack and closely fitting with crack without loosening. As was shown in figure 3.

![Figure 3. Concrete-specimen with wedge](image)
2.3 Chloride ion erosion test
Firstly, loaded concrete was soaked in pure water in order to achieve water saturation state, and then it was removed in 8% NaCl. After reaching predetermined erosion days, cracked concrete specimens were removed from chloride ion solution. Specimens were cut along the crack direction and divided into two parts.

Half of specimens were drilled to measure chloride ions content at different depths, as was shown in figure 4. Take samples from exposed surface 5mm depth with 3mm diameter drill bit, and take each layer powder sample for every 10mm up to 50mm or 80mm along the depth direction and remove powder samples on both sides. Chloride ions content in each layer powder was calculated according to the water transport engineering concrete test code (JTJ270-98)[12]. Chlorine ion content can be obtained by the following formula and the chloride ion determination test was shown in figure 5.

\[
P(Cl^-) = \frac{C_{\text{AgNO}_3} \times V'_4 \times 0.03545}{G \times \frac{V_3}{40}}
\]

(1)

3. Test results and analysis
The loaded cracked concrete specimens were soaked in 8%NaCl for 30, 60 and 90 days. The surface chloride ion concentration \( C_s \) was fitted through MATLAB and the diffusion coefficient \( D_c \) was calculated. The stress intensity factor was calculated according to Data stress intensity factor manual.

3.1 Analysis of chloride ion concentration in different depths

![Figure 6](image_url)

Figure 6. Variation of chloride ion content with depth under initial crack loading
Figure 6 and Figure 7 show the chloride ion content change situation with the depth of cracked concrete respectively, when the load value applied by the testing machine in the three-point bending beam fracture test reaches the concrete crack initiation load and peak load. The average precast crack depth of cracked concrete specimens was 36.6mm. As it can be seen from the figure, the larger the loading value of three-point bending beam fracture test is, the higher the chloride ion content is. The content of chloride ions greater than the depth of precast fracture decreases with the increase of erosion depth. At the same depth, the chloride content of concrete specimens with wedge is significantly higher than that without wedge. It can be seen that compared with the chloride content at the depth of 40mm-50mm on 30d and 60d erosion times, the chloride content at the depth of 90d erosion times was significantly increased, indicating that from the initiation load level, erosion time was an important factor affecting the chloride content at the crack.

3.2 Chloride ion erosion profile analysis
Concrete erosion profile can be clearly observed by AgNO₃. Figure 8 shows chloride ion erosion section outline obtained by silver nitrate chromaticity method after 90d erosion times. The color of concrete section in black line is vermilion which shows chloride ion has not eroded this area. And the color outside line is gray-white, which indicates it has been eroded by chloride ion.

Table 3. Erosion area of concrete specimens

| Sample No. | Uneroded range (mm×mm) | Uneroded area/mm² | Sectional area/mm² | Erosion area/mm² | Percentage of erosion/% |
|------------|-------------------------|--------------------|--------------------|------------------|------------------------|
| 0-D90      | 8.2×4.4                 | 36.08              | 60                 | 23.92            | 39.87                  |
| S-2kN-D90  | 7.9×3.8                 | 30.02              | 60                 | 29.98            | 49.97                  |
| C-2kN-D90  | 7.7×3.8                 | 29.26              | 60                 | 30.74            | 51.23                  |
| S-CL-D90   | 7.5×3.5                 | 26.25              | 60                 | 33.75            | 56.25                  |
| C-CL-D90   | 6.8×3.8                 | 25.84              | 60                 | 34.16            | 56.93                  |
Table 3 shows the size and erosion ratio of specimens after 90d erosion times. It can be seen that erosion area of chloride ions increases under load, but there is no significant effect of continuous load on the increase of chloride erosion area. No matter under instantaneous or continuous load, the proportion of erosion area under initial load increased about 5% compared with that under pre-crack load, and the proportion of erosion area under failure load increased about 4% compared with that under crack load. But compared with instantaneous load, the erosion area under continuous load increased only 1.26%, 0.68% and 0.83% of 2kN, crack initiation load and failure load level, which indicates that load and load grade will affect the proportion of chloride ion erosion area of concrete, and whether the chloride ion erosion is under load holding state has little influence on proportion of chloride ion erosion area. The erosion area of cracked concrete specimens unloading account for only 40%, and that of the load holding concrete specimens account for about 50%. The proportion of fracture section erosion area increases significantly as long as crack initiation load of concrete is reached and which presents a slowly and steady trend growth with load increasing.

3.3 Analysis of chloride ion diffusion coefficient of cracked concrete under different load levels
Most scholars have proved that immersion condition of concrete chloride ion erosion conforms to Fick's second diffusion law. The formula of Fick's second law is as follows:

\[ C(x,t) = C_0 + (C_s - C_0) \left[ 1 - \operatorname{erf} \left( \frac{x}{2 \sqrt{D_c t}} \right) \right] \]

The chloride ion content measured at different depths was substituted into the above equation, and MATLAB was used to obtain the surface chloride ion concentration \( C_s \) and chloride ion diffusion coefficient \( D_c \) of the same concrete specimen, as was shown in Table 4.

| Sample No. | t/d  | \( C_s/\% \) | \( D_c \times 10^9/(m^2/s) \) | Sample No. | t/d  | \( C_s/\% \) | \( D_c \times 10^9/(m^2/s) \) |
|------------|------|--------------|----------------|------------|------|--------------|----------------|
| 0-D30      | 30   | 0.01287      | 4.64           | S-CL-D90   | 90   | 0.01430      | 2.13           |
| 0-D60      | 60   | 0.01263      | 2.36           | C-CL-D30   | 30   | 0.01649      | 2.48           |
| 0-D90      | 90   | 0.01481      | 0.79           | C-CL-D60   | 60   | 0.01514      | 1.89           |
| S-2kN-D30  | 30   | 0.01368      | 5.01           | S-CL-D90   | 90   | 0.01091      | 2.25           |
| S-2kN-D60  | 60   | 0.01312      | 2.2            | S-CL-D30   | 30   | 0.01247      | 9.72           |
| S-2kN-D90  | 90   | 0.01555      | 1.08           | S-CL-D60   | 60   | 0.01559      | 4.85           |
| S-2kN-D60  | 60   | 0.01277      | 5.92           | S-PL-D90   | 60   | 0.01555      | 4.85           |
| C-2kN-D30  | 30   | 0.01277      | 3.07           | C-PL-D30   | 30   | 0.01427      | 13.5           |
| C-2kN-D60  | 60   | 0.01187      | 0.84           | C-PL-D60   | 60   | 0.01761      | 3.96           |
| C-2kN-D90  | 90   | 0.01721      | 1.32           | * not detected due to test reasons. |
| C-CL-D30   | 30   | 0.01686      | 1.32           | C-CL-D90   | 90   | 0.01518      | 4.15           |
| C-CL-D60   | 60   | 0.01629      |                |            |      |              |                |

As it can be seen from the table 5, when load is less than cracking load, the diffusion coefficient is negatively correlated with erosion time, when load is greater than cracking load, with erosion time extended, diffusion coefficient increase continuously, because concrete specimens began to produce a series of micro-cracks under the crack initiation load, and the chloride ions erosion rate was accelerated. At the same time, the diffusion coefficient in concrete with wedge is larger than that without wedge under the same loading value, which indicates that inserting wedge in the crack will accelerate the erosion of chloride ion. According to the Data stress manual, the stress intensity factors of each concrete specimen are calculated. Table 5 shows the relationship between the stress intensity factor \( K \) and the diffusion coefficient \( D_c \) of each concrete specimen in 90d erosion times.
It can be seen from table 6, except for the concrete specimens numbered C-2kN-D90, chloride ion diffusion coefficient increases with stress intensity factor increasing. The reason of C-2kN-D90 specimen chloride ion diffusion coefficient is relatively small is that the surface chloride ion concentration value fitted by MATLAB is too large, which is 0.01721, much higher than the average level. When the surface chloride ion concentration of this concrete specimen is calculated by the average level value, it completely conforms to this law. The stress intensity factor reflects the strength of the stress field at the crack tip. The greater the stress intensity factor is, the more obvious the trend of instability expansion of concrete internal cracks is, which provides more channels for rapid erosion of chloride ions and increases the erosion rate of chloride ions, increasing the diffusion coefficient.

4. Conclusion
This experiment mainly analyzed chloride ion erosion of cracked concrete under different loading level, unloading and load holding conditions. The main conclusions are as follows:

(1) The loading level in fracture test of three-point bending beam has a significant impact on chloride ion content at the cracked section. At the same load level and depth, the chloride content of concrete with wedge is significantly higher than that without wedge.

(2) The load has a significant impact on the erosion area of chloride ions in the fracture section, and the erosion area proportion of the fracture section increased by about 15% after loading. When reached the concrete crack initiation load, the erosion area of the crack section increased slowly and steadily with the load increasing.

(3) When the external load is less than the crack initiation load, the chloride diffusion coefficient decreases with the erosion time increasing. When the external load is greater than the concrete crack initiation load, due to the generation of internal micro-cracks, chloride ion diffusion coefficient gradually shows a slow growth trend with erosion time increasing. Meanwhile, there is a positive correlation between the stress intensity factor and concrete chloride ion diffusion coefficient.

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