Study on Compressive Strength of Cracked Concrete under Chloride Ion Erosion

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Abstract. According to the orthogonal experimental design, the changes of compressive strength of shaft concrete with different lengths, widths and depths of cracks and different concentrations of sodium chloride solution were studied. The test results show that the higher the concentration of sodium chloride solution is, the stronger the compressive strength of concrete will be when the shaft concrete with fracture is soaked for 60 or 90 days. The order of cracks has the same order of influence on the compressive strength of concrete immersed in different concentrations of sodium chloride solution, that is, the depth of crack has the greatest influence, followed by the length, and the width has the least influence. The test combination with the minimum influence of crack on compressive strength of concrete is 4cm in length, 0.3mm in width and 1cm in depth.

1. Preface
With the development and utilization of coal resources in China and the increase in the service life of concrete shafts, the durability of shaft concrete structure has received more and more attention. During the construction of the wellbore, as the wellbore continues to grow, due to the combined effects of temperature, load, fatigue, and environmental corrosion, internal components such as misalignment and micro-cracks are damaged [1~2]. Therefore, the control and research of concrete cracks is a major issue in the shaft concrete engineering. The groundwater environment where the shaft concrete is located is rich in sulfate ions, bicarbonate ions and chloride ions, which are corrosive to concrete and cause serious chemical corrosion [3].

Domestic and foreign scholars have done the following research on the problem of the decline of durability of concrete structures caused by chloride ion erosive cracking concrete. For example, Zuo Guowang [4] studied the influence of crack on chloride ion content in concrete under the chloride salt erosion environment through the concrete chloride salt dry-wet cycle test experiment; Zhang Jun [5] used bending test to produce curved cracks with different widths in concrete beams. After immersing in 3% NaCl salt solution for a certain age, the core was sampled and the chloride ion content in the concrete at the crack was determined. The results show that the effect of cracks on chloride ion penetration in concrete is significant; Xu Zhaohui et al [6] carried out the dry-wet cycle soaking erosion test of chloride salt solution for concrete members subjected to self-anchored bending and cracking, and studied the flexural cracking members and The relationship between the degree of chloride ion erosion; Yan Yongdong et al. [7] summarized the durability variation of concrete structures under load cracks, non-load cracks and precast cracks under chloride environment, and
pointed out the influence of the parameters such as the crack form (artificial cracks, natural cracks), width, depth, spacing and other parameters on concrete permeability and chloride ion transport, internal steel corrosion; Ye et al [8] studied the crack width in the range with 0.05 mm to 0.20 mm, and considering the influence fracture morphology concrete admixture calculated variation chlorine ion diffusion coefficient concrete cracks according flow conservation law.

At present, the research on concrete corrosion mainly focuses on the corrosion mechanism of concrete and the change of mechanical properties of corroded concrete [9], and the research on the compressive strength of concrete under crack and corrosion is important and urgent. In this paper, the orthogonal test method is used to replace the comprehensive test with partial test to analyze the influence of concrete crack length, width and depth on the compressive strength of concrete under the action of sodium chloride corrosion. After analyzing the orthogonal test data, the order and salient features of the influencing factors are finally found [10].

2. Test materials and orthogonal test design

2.1. Test materials
In this test, the cement was used P.O42.5 ordinary Portland cement produced by Tangshan Jidong Cement Co. LTD of Hebei Province, the fine aggregate adopts natural river sand, and the gradation meets GB / T 14684-2011 "Construction sand" in medium sand II area requirements, and the other main performance indicators are: fineness modulus 2.6, loose bulk density 1840kg / m³, apparent density 2565kg / m³. The coarse aggregate is selected from 5 to 20 mm continuous grade gravel with gravel grade, and the apparent density is 2778 kg / m³. The concrete water reducing agent is a polycarboxylic acid water reducing agent with a solid content of 39% and a water reduction rate of 25%. The test water is tap water. The performance indexes of cement, fly ash and mineral powder are shown in Table 1.

| Raw material performance index parameters |  |
|----------------------------------------|---|
| **cement** | Variety | Setting time / min | Flexural strength / MPa | Compressive strength / MPa | Standard consistency water consumption (%) |
| | Initial condensation | Final condensation | 3d | 28d | 3d | 28d |
| P.O.42.5 | 140 | 230 | 5.22 | 7.6 | 19.1 | 51.0 | 28.0 |
| Class II fly ash | Fineness % | Water demand ratio /% | Loss on ignition /% | Density / (g·cm⁻³) | SO₃ content /% |
| 12.5 | 100 | 6.8 | 2.5 | 1.35 |
| S95 slag powder | Density / (g·cm⁻³) | Specific surface area / (m²·kg⁻¹) | Loss on ignition /% | 28d activity index /% | SO₃ content /% | Liquidity /% |
| 2.89 | 416 | 1.6 | 98 | 2.13 | 97 |

2.2. Orthogonal test design
The effects of the length, width and depth of the crack and the level of each factor on the compressive strength of the concrete will be tested. Three main factors, namely the length, width and depth of the concrete crack, were set to three levels respectively, so that the orthogonal test of L₉ (3⁴) was designed. Table 2 shows the factor levels, Table 3 orthogonal test protocol.
Table. 2 Factor Level Table

| Level | Factor     |
|-------|------------|
|       | A length / cm | B width / mm | C depth / cm |
| 1     | 4           | 0.3          | 1           |
| 2     | 5           | 0.4          | 2           |
| 3     | 6           | 0.5          | 3           |

Table. 3 Orthogonal experimental scheme

| Experimental group number | Horizontal combination | Factor     |
|---------------------------|------------------------|------------|
|                           |                        | A length / cm | B width / mm | C depth / cm | D/empty |
| 1                         | A₁B₁C₁                 | 1(4)        | 1 (0.3)      | 1(1)         | 1       |
| 2                         | A₁B₂C₂                 | 1(4)        | 2 (0.4)      | 2(2)         | 2       |
| 3                         | A₁B₃C₃                 | 1(4)        | 3 (0.5)      | 3(3)         | 3       |
| 4                         | A₂B₁C₂                 | 2(5)        | 1 (0.3)      | 2(2)         | 3       |
| 5                         | A₂B₂C₃                 | 2(5)        | 2 (0.4)      | 3(3)         | 1       |
| 6                         | A₂B₃C₁                 | 2(5)        | 3 (0.5)      | 1(1)         | 2       |
| 7                         | A₂B₃C₃                 | 3(6)        | 1 (0.3)      | 3(3)         | 2       |
| 8                         | A₃B₂C₁                 | 3(6)        | 2 (0.4)      | 1(1)         | 3       |
| 9                         | A₃B₃C₂                 | 3(6)        | 3 (0.5)      | 2(2)         | 1       |

The concrete test block used in the test was 100mm×100mm×100mm, and the corresponding crack was made according to the orthogonal test design. According to the national standard GB/T 50081-2002 "Standard for the test of mechanical properties of ordinary concrete", the standard test block is made. After the test block is formed, it is put into the standard curing room and the standard curing is 28 days. The test block is immersed in water and the concentration is 10% NaCl and 15% NaCl solution, the compressive strength of the concrete was measured for 60, 90d. The concrete mix ratio is shown in Table 4.

Table. 4 Concrete mix ratio (kg/m³)

| cement   | Fly ash | Mineral powder | sand | Stone | water | Water reducing agent |
|----------|---------|----------------|------|-------|-------|----------------------|
| 372      | 48      | 112            | 632  | 1075  | 160   | 5.32                 |

3. Test results and analysis

3.1. Orthogonal test results
According to the above test scheme design, the compressive strength of cracked concrete test blocks in different soaking ages and different concentrations of NaCl solution was measured. The test results are shown in Table 5.
3.2. Analysis of concrete compressive strength

The curves of compressive strength of concrete with cracks at different ages as a function of solution concentration are shown in Fig 1 and Fig 2.

### Table 5 Orthogonal test results

| Test number | Orthogonal combination | Compressive strength / MPa |
|-------------|------------------------|-----------------------------|
|             |                        | Water 10% NaCl | 15% NaCl | Water 10% NaCl | 15% NaCl |
| 1           | A1B1C1                 | 65.46          | 68.48    | 70.24          | 66.22    | 71.82    | 72.10    |
| 2           | A1B2C2                 | 62.37          | 63.87    | 65.38          | 63.41    | 66.54    | 67.41    |
| 3           | A1B3C3                 | 59.64          | 62.36    | 63.04          | 61.73    | 65.12    | 65.22    |
| 4           | A2B1C2                 | 61.13          | 63.44    | 65.17          | 63.94    | 66.71    | 67.24    |
| 5           | A2B2C3                 | 60.76          | 62.67    | 62.10          | 61.63    | 64.82    | 65.34    |
| 6           | A2B3C1                 | 62.34          | 66.76    | 66.5           | 66.10    | 67.00    | 66.51    |
| 7           | A3B1C2                 | 61.14          | 61.57    | 61.27          | 61.92    | 63.21    | 63.92    |
| 8           | A3B2C1                 | 64.47          | 65.28    | 65.94          | 66.31    | 66.92    | 67.00    |
| 9           | A3B3C2                 | 59.62          | 62.37    | 63.01          | 61.44    | 64.33    | 66.61    |

Fig. 1 Compressive strength of concrete when soaked for 60d

Fig. 2 Compressive strength of concrete when soaked for 90d
It can be seen from Fig. 1 and Fig. 2 that the compressive strength of concrete with cracks immersed in 10% NaCl and 15% NaCl solution for 60d and 90d is higher than that of concrete immersed in the reference group, and the compressive strength of concrete with immersion age of 90d is higher than the compressive strength of concrete with an immersion age of 60d. Compared with the compressive strength of cracked concrete immersed in water, when the immersion age is 60d and the NaCl solution concentration is 10%, the compressive strength of concrete with crack length of 5cm, width of 0.5mm and depth of 1cm (A2B3C1) increases the most and increased by 7.1%; when the immersion age is 60d and the NaCl solution concentration is 15%, the concrete with the crack length of 6cm, the width of 0.5mm and the depth of 2cm (A3B3C2) has the highest compressive strength, which is increased by 7.9%; Compared with the immersion age of 90d, the compressive strength of concrete with crack length of 4cm, width of 0.3mm and depth of 1cm (A1B1C1) immersed in 10% NaCl solution and 15% NaCl solution increased the maximum, increasing by 8.5% and 8.9%.

As the concrete age increases and the concentration of sodium chloride solution increases, chloride ions enter the concrete through osmosis, and the chloride ions react with the hydrated product calcium hydroxide to form insoluble hydrated calcium chloroaluminate, which is filled into the pores of the concrete, the compactness of the concrete increases, which increases the compressive strength of the concrete. When the concentration of the soaked NaCl solution is 10% and 15%, the higher the concentration difference between the inside and outside of the concrete. The faster and more the chloride ion is transported into the concrete, the more hydration products are produced, and the concrete is filled. The more filler the void has, the denser the concrete and the greater the increase in compressive strength. When the immersion age increases from 60d to 90d, as the age increases, the more hydration products inside the concrete, the internal pores are fully filled, and the compressive strength of the concrete increases.

3.3. Orthogonal test results range and variance analysis
In order to further analyze the primary and secondary order of the effect of crack on concrete compressive strength, the test results of concrete compressive strength immersed in water, 10% NaCl and 15% NaCl solution were analyzed. The results of the range analysis are shown in Figures 3 and Figures 4.

![Factor diagram of 60d index of cracked concrete immersion](image)

**Fig. 3** Factor diagram of 60d index of cracked concrete immersion
It can be seen from Fig. 3 and Fig. 4 that the primary and secondary order of cracks on the compressive strength of concrete immersed in water, 10% NaCl and 15% NaCl solution for 60d and 90d respectively, i.e. crack depth—crack length—crack width. It can also be seen from the index factor graph that the minimum combination of crack's influence on the compressive strength of the concrete is A1B1C1, that is, the crack length is 4 cm, the width is 0.4 mm, and the depth is 1 cm.

In order to further analyze the significance of crack length, width and depth on concrete compressive strength, the test results of concrete compressive strength immersed in 10% NaCl and 15% NaCl solution were analyzed by variance. The results of the analysis of variance are shown in Tables 6 and Tables 7.

**Table. 6** Analysis of variance of orthogonal test results of concrete compressive strength in 10% NaCl solution

| factor | 60d | 90d | F-threshold |
|--------|-----|-----|-------------|
|        | Sum of squared deviation | Degree of freedom | F value | Sum of squared deviation | Degree of freedom | F value |  |
| Length A | 5.205 | 2 | 5.234 | 16.072 | 2 | 5.099 | F0.1(2,2)=9 |
| Width B | 0.766 | 2 | 0.771 | 5.244 | 2 | 1.664 | F0.05(2,2)=19 |
| Depth C | 35.640 | 2 | 35.837 | 23.644 | 2 | 7.501 | F0.025(2,2)=39 |
| Error D | 0.994 | 2 | 3.152 | 2 |  |

**Table. 7** Variance Analysis Table of Orthogonal Test Results of Concrete Compressive Strength in 15% NaCl Solution

| factor | 60d | 90d | F-threshold |
|--------|-----|-----|-------------|
|        | Sum of squared deviation | Degree of freedom | F value | Sum of squared deviation | Degree of freedom | F value |  |
| Length A | 11.972 | 2 | 14.801 | 10.873 | 2 | 2.422 | F0.1(2,2)=9 |
| Width B | 3.160 | 2 | 3.907 | 5.090 | 2 | 1.134 | F0.05(2,2)=19 |
| Depth C | 44.334 | 2 | 54.809 | 25.755 | 2 | 5.737 | F0.025(2,2)=39 |
| Error D | 0.809 | 2 | 4.489 | 2 |  |
It can be seen from Table 6 that the cracked concrete immersed in 10% NaCl solution for 60 days has a depth factor of $F_{0.05} < F$, indicating that the depth of the crack has a significant influence on the compressive strength of the concrete, and the length and width $F < F_{0.1}$, indicating the length and the width have little effect on the compressive strength of concrete; the cracked concrete immersed in 10% NaCl solution for 90d, the $F$ value of length, width and depth are less than $F_{0.1}$, indicating the length, width and depth of the crack to the concrete compressive strength have less affected. It can be seen from Table 7 that the cracked concrete immersed in 15% NaCl solution for 60 days has a depth factor of $F_{0.025} < F$, indicating that the depth of the crack has a significant effect on the compressive strength of the concrete, and the length factor $F_{0.1} < F < F_{0.025}$, indicating that the compressive strength of the length concrete has a significant influence, but the width factor $F < F_{0.1}$, indicating that the crack width has little effect on the compressive strength of the concrete; the cracked concrete immersed in a 15% NaCl solution for 90 days, the $F$ value of length, width and depth are less than $F_{0.1}$, indicating that the length, width and depth of the crack have little effect on the compressive strength of the concrete, but the depth factor is still greater than the length factor and the width factor. The effect of crack length, width and depth on the compressive strength of concrete immersed in NaCl solution by variance analysis is: depth $> \text{length} > \text{width}$.

There are two sources of error for the orthogonal test. One is the model error, and the other is the test error. It can be seen from the variance analysis of other groups of test results that the model error is relatively small. The results of variance analysis of compressive strength of concrete with cracks immersed in 10% NaCl solution for 90 days are likely to be derived from experimental errors. The results of variance analysis show that the length, width and depth of the crack have little effect on the compressive strength of the concrete, but the $F$ value of the depth factor is much larger than 1, which is statistically significant. So it can still reveal that the crack has the same effect on the compressive strength of the concrete, i.e. the impact of the depth is highest, the length is second, and the width is minimal.

4. Conclusion

(1) The compressive strength of concrete with cracks immersed in 10% NaCl and 15% NaCl solution for 60d and 90d have the same rule of change, that is, as the concentration of solution increases, the longer the immersion age, the greater the compressive strength of concrete.

(2) Orthogonal test range analysis showed that the crack depth was the most influential factor for the compressive strength of cracked concrete immersed in 10% NaCl and 15% NaCl solution for 60d and 90d, and the crack was resistant to concrete. The smallest test combination for the influence of compressive strength is $A_1B_1C_1$, i.e. the crack length is 4 cm, the width is 0.3 mm, and the depth is 1 cm.

(3) The results of orthogonal test variance analysis showed that for cracked concrete immersed in 10% NaCl and 15% NaCl solution for 60d and 90d, the influence of crack depth on compressive strength was the highest, followed by length and width was the smallest.

(4) The results of orthogonal test range analysis are in good agreement with the results of variance analysis. The effect of crack factors on the compressive strength of the index shows that depth is the most influential factor with high significance [1].

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