Article

Study on Mechanical Properties and Constitutive Relationship of Concrete Corroded by Hydrochloric Acid under Cyclic Load

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Abstract: Most of the existing studies on acid corrosion of concrete have focused on the mechanical behavior of concrete structures under monotonic load or without load. To investigate the mechanical properties of in-service concrete components under cyclic load in an acid corrosion environment, six groups of concrete prism specimens with different acid corrosion degrees (corrosion duration) were designed and prepared by the accelerated corrosion test method. The monotonic and cyclic axial compression load tests on these specimens were conducted to investigate the effects of corrosion degree on the mechanical properties of concrete specimens. The experimental results indicated that hydrochloric acid corrosion has obvious effects on the failure characteristics and mechanical properties of concrete. The surface of corroded concrete was easier to crack and spall under load, and the concrete spalling area enlarged as the acid corrosion duration increased. The compressive capacity of concrete specimens reduced rapidly with the increase in corrosion duration. The stress–strain envelope curves for concrete with different corrosion duration under cyclic load were essentially similar to that of concrete under monotonic load. The degradation rate of the descending section for the stress–strain curves of corroded concrete under cyclic load was much larger than that under the monotonic load due to the accumulation of internal damage in concrete. The peak strain and ultimate strain of corroded concrete increased significantly with the increase in corrosion duration and enhanced by 55.7% and 77.9%, respectively, compared with the uncorroded concrete, whereas the peak stress and elastic modulus rapidly decreased and reduced by 53.3% and 74.1%, respectively. Moreover, based on the strength degradation depth, the concept of effective bearing cross-sectional area ratio was proposed to characterize the corrosion degree of concrete, and the correction coefficient of descending section for the effective bearing cross-sectional area ratio was introduced to establish the constitutive model of corroded concrete under cyclic load, and the results calculated by this model matched well with the experimental values. The research in this paper can provide the experimental and theoretical basis for seismic life cycle and fatigue redesign of concrete structures in acid corrosion environments or coastal areas.

Keywords: corrosion degree; cyclic load; concrete prism specimens; constitutive relationship; mechanical properties

1. Introduction

In recent decades, reinforced concrete (RC) has been widely used in real engineering as a common material due to its good durability, economy, and safety. Concrete carbonation, freeze–thaw cycles, steel corrosion, and salt erosion were the main factors affecting the durability of RC structures. Meanwhile, the durability of concrete caused by acid corrosion was still one of the crucial factors restricting its sustainable development. In particular, the concrete members in the sulfuric acid or hydrochloric acid corrosion environment [1–6]. Several investigations indicated that acid corrosion had become one of the major threats
affecting the mechanical properties of RC structures [7–12], resulting in the reduction of bearing capacity and ductility. Meanwhile, the double coupling actions of acid corrosion and load not only affected the durability of concrete structures but also made the calculation method used in the existing design no longer applicable to the concrete severely corroded by acid, endangering the safety of structures. As a result, the influences of acid corrosion on concrete structures could not be neglected.

For this purpose, some scholars have conducted numerous works on the acid corrosion concrete components, including the corrosion types of concrete [7,13], corrosion mechanism [14], influencing factors of acid corrosion [15–20], and the interaction mechanism of various factors [21–24], as well as the impacts of stress state and damage layer [24–27] on the mechanical properties of corroded concrete. It was found that acid was one of the main corrosive mediums for concrete structures, which seriously reduced the bearing capacity of concrete structures and thus changed the failure mechanism of concrete structures. In addition, industrial production would discharge a large number of acidic gases and industrial waste liquid containing many acidic substances, especially in the coastal and western regions of China [28,29]. In these areas, the concentration of chloride ions and sulfates in the environment was high, and the erosion of concrete by sulfates [30–33] and the corrosion of steel bars in concrete by chlorides [34] would rapidly degrade the performance of reinforced concrete structures. It seriously affects the normal application and durability of RC structures.

At present, there is much available literature on acid corrosion concrete, and it has mostly focused on the mechanical properties of acid corrosion concrete components without load or under monotonic load [18,25,35]. Chen et al. [18] studied the mechanical properties such as the compressive strength, elastic modulus, and the variation laws of the stress–strain curves for concrete corroded by hydrochloric acid corrosion with PH 2 and 3, and revealed the internal mechanism for the performance degradation of hydrochloric acid corroded concrete. Huang [35] conducted uniaxial compression load tests on concrete test specimens corroded by acid or inorganic salt and the stress–strain curves of concrete obtained by constant strain rate loading. However, in practical engineering, a large number of existing concrete structures were often subjected to cyclic loads, such as seismic action, fatigue load, wind load, etc. Meanwhile, there was also a coupling effect between corrosion damage and fatigue damage for RC structures [36–38]. In relevant literature reviews [13–17,23–26], some research studies on the acid concrete under cyclic load have been examined, including the mechanical properties [11,15,22,26,38] and modeling constitutive relationship [16,24,25,32,35] of sulfate-attacked concrete. There are few reports on the mechanical properties, and constitutive relationship of hydrochloric acid corroded concrete under cyclic load [2,5,18]. Consequently, it was necessary to investigate the variation laws of mechanical properties and the constitutive relationship of in-service concrete components under cyclic load in the hydrochloric acid corrosion environment. Furthermore, the influence of acid corrosion duration on the performance degeneration of concrete structures needs to be further discussed.

To this end, considering the gaps in existing research, the corrosion degree (duration) of hydrochloric acid was regarded as the main parameter in this paper; six groups of concrete prism specimens with different acid corrosion degrees (duration) were designed and prepared by the accelerated corrosion test method. Then, the monotonic and cyclic axial compression load tests were carried out on these specimens to examine the effect of corrosion duration on the mechanical properties of acid-corroded concrete specimens. The mechanical properties such as the failure modes, stress–strain curves, concrete strength, elastic modulus, peak strain, and ultimate strain of uncorroded concrete and corroded concrete with different acid corrosion degrees were tested and analyzed. Moreover, based on the strength degradation depth, the concept of effective bearing cross-sectional area ratio was proposed to characterize the corrosion degree of concrete, and the correction coefficient of descending section for the effective bearing cross-sectional area ratio was introduced to establish the modified constitutive model of concrete corroded by hydrochloric acid under
cyclic load. The results calculated by using the modified model matched well with the test results. The research in this paper can provide the experimental and theoretical basis for seismic life cycle and fatigue redesign of concrete structures in acid corrosion environments or coastal areas, such as the design and maintenance of dams, port hydraulic structures, highways, and bridges in coastal areas.

2. Experimental Program

2.1. Specimen Preparation

According to the Chinese codes GB/T50082-2009 and GB/T50081-2002, six groups of concrete prism specimens with the dimensions of 100 mm × 100 mm × 300 mm were designed, and they were labeled as F0–F5. To consider the discreteness of concrete, 6 identical concrete specimens were cast in each group. As a result, a total of 36 concrete prism specimens were prepared for the compression load tests. The design strength of concrete was C30 for all test specimens in this test, which was consistent with the concrete grade of the in-service concrete components possibly. The C30 concrete material was mainly composed of 32.5 R ordinary Portland cement, medium sand, ordinary crushed stone with grain size less than 18 mm, ordinary domestic water, etc. The water–binder ratio \( \frac{m_w}{m_c} \) was chosen as 0.4 for each specimen, and the detailed mix ratio and amount of the materials are summarized in Table 1. Moreover, the measured compressive strength of the cubic concrete specimens without hydrochloric acid corrosion after 28 d of curing was 31.3 MPa, and the elastic modulus was \( 3.03 \times 10^4 \) MPa.

Table 1. Amount of each material (Units: kg/m\(^3\)).

<table>
<thead>
<tr>
<th>( \frac{m_w}{m_c} )</th>
<th>Cement</th>
<th>Water</th>
<th>Medium Sand</th>
<th>Crushed Stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>450</td>
<td>180</td>
<td>563</td>
<td>1148</td>
</tr>
</tbody>
</table>

2.2. Corrosion Test

The hydrochloric acid corrosion tests on these specimens after 28 days of curing were conducted by using the accelerated corrosion test method. The accelerated corrosion test method was considered to be a common method for the acid corrosion of concrete specimens in the laboratory, which was used to simulate the long-term acid corrosion process of concrete in a practical project possibly. Meanwhile, the corrosion duration of concrete can be shortened significantly using the accelerated corrosion test method, and the feasibility and effectiveness of the accelerated corrosion method were verified by some available investigations [39–42]. As a result, the specimens were fully immersed in the corrosion solution of 1% hydrochloric acid (mass fraction) and replaced the corrosion solution every two days to maintain the constant corrosion environment for corroded specimens. However, six specimens in the F0 group were not corroded by hydrochloric acid. In this case, the corrosion durations were chosen as 0 d, 6 d, 12 d, 18 d, 24 d, and 30 d, respectively, for the F0–F5 group specimens to investigate the impacts of various corrosion durations on the mechanical properties of concrete specimens. There were six specimens in each group; three specimens were used to conduct the monotonic compression load test, whereas the other three specimens were carried out for the cyclic compression load test. The detailed specimen number and loading conditions are listed in Table 2.
Table 2. Detailed information on test specimens.

<table>
<thead>
<tr>
<th>Corrosion Duration/d</th>
<th>Monotonic Compression Specimens No.</th>
<th>Cyclic Compression Specimens No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>F0-1; F0-2; F0-3</td>
<td>F0-4; F0-5; F0-6</td>
</tr>
<tr>
<td>6</td>
<td>F1-1; F1-2; F1-3</td>
<td>F1-4; F1-5; F1-6</td>
</tr>
<tr>
<td>12</td>
<td>F2-1; F2-2; F2-3</td>
<td>F2-4; F2-5; F2-6</td>
</tr>
<tr>
<td>18</td>
<td>F3-1; F3-2; F3-3</td>
<td>F3-4; F3-5; F3-6</td>
</tr>
<tr>
<td>24</td>
<td>F4-1; F4-2; F4-3</td>
<td>F4-4; F4-5; F4-6</td>
</tr>
<tr>
<td>30</td>
<td>F5-1; F5-2; F5-3</td>
<td>F5-4; F5-5; F5-6</td>
</tr>
</tbody>
</table>

2.3. Test Setup

In this test, the electro-hydraulic servo material testing machine was produced by China Shanghai New Think Measurement Instrument Manufacturing Co., LTD., and it was used to conduct the uniaxial compression load tests of concrete specimens in the structural laboratory. The maximum pressure force was 300 tons capacity, the accuracy was 0.1 kN, and the automatic dynamic control mode was set up before the test. Figure 1 shows the test loading device of specimens. According to the Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T50081-2002), two steel plates parallel to the bottom and top of the specimen in the machine were selected to apply the vertical load, and the two loaded surfaces of each specimen were polished to ensure that the bottom and upper of concrete were perpendicular to the test machine’s axis. Before loading, a layer of butter was smeared on the interaction surface between the specimen and steel plate to reduce or avoid the influence of friction between the specimen’s end surface and the steel plate of loading and simulate the concrete specimen under uniaxial compression, possibly [18, 25, 27, 35]. Preloading was performed before the formal test to eliminate the initial inelastic deformation.

![Test loading device diagram](image-url)

**Figure 1.** Test loading device diagram: (a) photograph of loading and (b) three-dimensional diagram of the loading device.

The variation laws of the stress–strain relationship curves of concrete corroded by hydrochloric acid were obtained mainly in the test from the perspective of static load, and thus the test was controlled by displacement load to investigate the mechanical properties of concrete specimens with various corrosion durations. After the pre-loading, the vertical pressure force with a speed of 0.3 mm/min was applied during the monotonic load. Once the vertical stress reached the predicted peak value of 70~90% (12 N/mm²), the loading speed was reduced to 0.1 mm/min until the specimen was destroyed. Meanwhile, the cyclic load tests of specimens were carried out by adapting the displacement control method similar to the monotonic load. To this end, the displacement control was performed, and the
speed was selected as 0.3 mm/min during loading, and the displacement increment was 0.05 mm. However, force control was adopted for the unloading stage, and the unloading speed was 3 kN/s until the specimen failed. The loading mechanism of the cyclic load is shown in Figure 2.

![Figure 2. The loading mechanism of cyclic load.](image)

2.4. Strength Degradation Depth

To further study the damage degree of corroded concrete, two hypotheses were proposed based on the results of [19,21,24,25,32] as follows: (1) The concrete corroded by the hydrochloric acid solution developed evenly from the outer surface to the inner surface of the concrete. That is, the depth of each corrosion layer \( d_f \) of the same test specimen was identical. (2) The hydrochloric acid corrosion concrete included two layers, which were composed of an evenly distributed corroded layer, \( S_1 \), and an uncorroded layer \( S_2 \), as shown in Figure 3. The boundary between the two layers was obvious, and the vertical load was only provided by the uncorroded layer of concrete. As a result, the depth of the corrosion layer was the same as the strength degradation depth.

![Figure 3. Hydrochloric acid corrosion diagram of concrete.](image)

According to the characteristics of concrete in a corroded layer that could not bear the load and the boundary strain coordination between the corroded layer and uncorroded layer of concrete, the calculation formula of strength degradation depth was determined by Equation (1):

\[
\frac{F_0}{ab} = \frac{F_n}{(a - 2d_f)(b - 2d_f)}
\]

(1)

where \( F_0 \) represents the compressive capacity of the uncorroded concrete cross-section, and \( F_n \) is the compressive capacity of the corroded concrete cross-section. \( a \) stands for the short side length of the concrete cross-section, and \( b \) is the long side length of the concrete. \( d_f \) represents the theoretical strength degradation depth.
In this experiment, \( b = a = 100 \), and thus, the \( d_f \) was simplified to Equation (2):

\[
    d_f = 50\left(1 - \sqrt{\frac{F_n}{F_0}}\right)
\]  

(2)

3. Performance of Concrete Specimens under Monotonic Load and Cyclic Load

3.1. Failure Mode of Concrete Specimen

Figure 4 shows the failure modes of specimens with various hydrochloric acid corrosion durations under monotonic and cyclic loads. It can be seen from Figure 4 that the failure modes of all test specimens under monotonic and cyclic loads were essentially similar, which presented that the concrete was crushed severely; that is, the concrete specimens reached the ultimate compressive strain and, thus, the specimen failure. During loading, the first visible vertical crack appeared on the concrete surface when the vertical load reached 60% or 70% of the concrete compressive strength. As the load increased, several new cracks emerged and extended gradually, the number of cracks increased significantly, and the width of cracks enlarged rapidly. When the load approached the compressive strength, the concrete specimen was divided into several blocks by penetrating cracks and seriously crushed, and the vertical deformation was relatively larger. As can be seen in Figure 4a,b, there was no significant difference in the failure mode between the uncorroded concrete specimen (F0) and the concrete specimen with a corrosion duration of 6 d (F1). Large areas of concrete spalling were observed, and the crack extension and propagation in F0 and F1 were sufficient. When the acid corrosion duration reached 12 d or 18 d, some short and narrow, and irregular cracks were found at the concrete specimen’s surface under axial compression, and several micro-cracks appeared inside the concrete. Meanwhile, the concrete specimen has a local crushing phenomenon, large areas of concrete were crushed, and the crack extension and evolution of F2 and F3 were relatively insufficient compared to the uncorroded specimens F0, as depicted in Figure 4c,d. For acid-severely corroded concrete specimens F4 and F5 (corrosion durations of 24 d and 30 d), a large number of obvious cracks rapidly developed after the first crack (main crack) appeared, and the main crack continued to extend and widen. When the concrete specimen was close to failure, the surface of the concrete showed drum-shaped, and the main vertical crack penetrated the specimen, with a width of around 3 mm, as shown in Figure 4e,f.

![Figure 4. Cont.](image-url)
3.2. Stress–Strain Curves of Corroded Concrete under Monotonic Load

As noted previously, three specimens in each group showed similar failure modes under monotonic load, and thus one concrete specimen in each group was selected for comparative analysis of stress–strain curves. The stress–strain curves of uncorroded concrete and concrete with various acid corrosion durations under monotonic load are shown in Figure 5a. To analyze and compare these curves preferably, Figure 5b shows the typical uniaxial compression stress–strain curve of the specimen in a dimensionless coordinate system. From Figure 5a, the variation laws of the stress–strain curves for concrete at each corrosion duration were essentially similar. As can be seen in Figure 5b, the stress–strain curve of uncorroded and corroded concrete specimens under uniaxial compression load could be generally divided into five sections, including the linear elastic section at points A,B, the nonlinear ascending section at points B,C, the nonlinear descending section at points C,D, the reverse bending section at points D,E, and the complete failure section after point E. Point C represented the peak stress point of the specimen, and the relative strain $\varepsilon/\varepsilon_c$ was 1. Point D was the approximate inflection point of the curve.

In the ascending section at points A,C, the micro-cracks of the specimen formed and developed independently. After the load reached the peak stress, the plastic deformation of the concrete began to increase rapidly, and the stress–strain curve of the concrete entered the descending section. The curve of the descending section was slightly steep, and the micro-cracks expanded steadily. Meanwhile, the first small visible crack appeared at the corner of the specimen surface. The stress drastically decreased with the further increase in strain, and the crack propagation and development entered the unstable expansion stage. While the first crack continued to develop and widen, other cracks bifurcated and penetrated the surface and gradually formed larger cracks. Meanwhile, the stress quickly
decreased, showing the softening effect after the peak stress. When the stress dropped to 0.5 times the peak stress, the slope of the curve decreased rapidly, and the curve became very flat. In the complete failure section after point E, the main cracks penetrated the concrete specimen. Finally, the concrete surface was characterized by obvious macroscopic cracks. It was also found that when the uniaxial load was smaller, the concrete had a certain self-healing ability [43], and the concrete specimen was essentially in the linear elastic section (AB), and there was almost no crack inside the concrete, which has little influence on the stress–strain curve of concrete. However, as the load increased, some new cracks gradually formed and developed. Meanwhile, the concrete was in the elastic-plastic section (BC), and the internal structure was damaged to a certain extent. When the destruction exceeded the damage threshold of concrete, the self-healing ability of the concrete material was weakened [44], and the bearing capacity of concrete specimens rapidly decreased (CE).

In addition, it can also be seen from Figure 5a that with the increase in corrosion duration, the peak stress of concrete decreased obviously, whereas the peak strain increased gradually. The differences between the stress–strain curve of acid-corroded concrete and uncorroded concrete mainly lie in the peak point downward and backward deviation. That is, as the corrosion duration increased, the shape of stress–strain curves tended to flat, and the initial slope of the curve gradually decreased. The slope of the ascending section obviously decreased, and the descending section of the curve became flat. In general, the concrete specimen corroded by hydrochloric acid showed a trend of loosening, and the peak stress and elastic modulus decreased gradually. For concrete specimens with hydrochloric acid corrosion severely, the peak strain and ultimate strain were significantly increased compared with the uncorroded concrete.

![Stress-strain curves of concrete specimens corroded by hydrochloric acid under monotonic load](image)

**Figure 5.** Stress–strain curves of concrete specimens corroded by hydrochloric acid under monotonic load: (a) Monotonic compressive stress–strain curves for concrete specimens with various corrosion durations and (b) Stress–strain normalized curves of the typical concrete specimen under monotonic load.

### 3.3. Stress–Strain Curves of Corroded Concrete under Cyclic Load

Similarly, one concrete specimen in each group was used to investigate the influence of acid corrosion duration on the stress–strain curves of concrete under cyclic load due to the variation law of stress–strain curves for three specimens in each group being identical. The stress–strain normalized curves of concrete specimens with different acid corrosion durations are shown in Figure 6. To facilitate comparative analysis, Figure 6 also depicts the envelope of the stress–strain curve for each concrete specimen (As seen in the blue real line). As can be seen in Figure 6, the variation law of the stress–strain curve of acid-corroded concrete under cyclic load was similar to these specimens under monotonic load. As the corrosion duration increased, the stress–strain curve of concrete gradually tended to be flat, and the peak stress significantly reduced, while the ultimate strain and peak strain increased gradually, and the strength and bearing capacity of concrete remarkably decreased.
Figure 6. Stress–strain normalized curves of concrete specimens with different acid corrosion durations under cyclic load: (a) 0 d; (b) 6 d; (c) 12 d; (d) 18 d; (e) 24 d; (f) 30 d.

3.4. Mechanical Properties of Characteristic Values Analysis

The test results of mechanical properties for concrete specimens F0–F5 under monotonic load are summarized in Table 3. The peak stress represented the maximum stress of the stress–strain curve, the peak strain was the strain corresponding to the peak stress, and the elastic modulus of concrete was calculated by using the secant modulus between the origin point (“0” point) and the 0.4 $f_c$ point on the stress–strain curve ($f_c$ represents the peak stress of curve). The peak displacement was the displacement corresponding to the peak load, and the ultimate strain was the compressive strain corresponding to the stress when the stress was dropped to 0.5 of its peak stress [45]. As can be seen in Table 3, the strength degradation depth steadily increased with the increase in acid corrosion duration, and the mechanical properties of concrete were obviously affected by the corrosion duration. In this case, the elastic modulus and peak stress of concrete gradually decreased, whereas...
the peak strain and ultimate strain increased significantly. Compared with the uncorroded specimen (F0), the elastic modulus and peak stress of concrete rapidly decreased as the corrosion duration increased and decreased by 73.9% and 53.3%, respectively. Meanwhile, the peak strain and ultimate strain increased significantly, with a maximum increase of 52.1% and 69.4%, respectively.

Table 3. Test results of all concrete specimens under monotonic load.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Corrosion Duration/d</th>
<th>Peak Load/kN</th>
<th>Peak Displacement/mm</th>
<th>Ultimate Displacement/mm</th>
<th>Peak Stress/MPa</th>
<th>Peak Strain/×10^{-6}</th>
<th>Ultimate Strain/×10^{-6}</th>
<th>Elastic Modulus/×10^4 MPa</th>
<th>Strength Degrada- tion Depth/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>0</td>
<td>276.6</td>
<td>0.79</td>
<td>1.10</td>
<td>27.66</td>
<td>2633</td>
<td>3656</td>
<td>2.18</td>
<td>0</td>
</tr>
<tr>
<td>F1</td>
<td>6</td>
<td>248.7</td>
<td>0.84</td>
<td>1.29</td>
<td>24.87</td>
<td>2800</td>
<td>4316</td>
<td>1.98</td>
<td>1.65</td>
</tr>
<tr>
<td>F2</td>
<td>12</td>
<td>226.9</td>
<td>0.87</td>
<td>1.32</td>
<td>22.69</td>
<td>2900</td>
<td>4409</td>
<td>1.52</td>
<td>4.56</td>
</tr>
<tr>
<td>F3</td>
<td>18</td>
<td>211.9</td>
<td>0.92</td>
<td>1.45</td>
<td>21.19</td>
<td>3067</td>
<td>4834</td>
<td>1.27</td>
<td>5.92</td>
</tr>
<tr>
<td>F4</td>
<td>24</td>
<td>155.4</td>
<td>1.02</td>
<td>1.53</td>
<td>15.54</td>
<td>3400</td>
<td>5094</td>
<td>0.98</td>
<td>9.62</td>
</tr>
<tr>
<td>F5</td>
<td>30</td>
<td>129.3</td>
<td>1.23</td>
<td>1.95</td>
<td>12.93</td>
<td>4100</td>
<td>6502</td>
<td>0.57</td>
<td>15.73</td>
</tr>
</tbody>
</table>

The variation trends of the elastic modulus, peak stress, peak strain, and ultimate strain of concrete with different corrosion durations are depicted in Figure 7. As can be seen in Figure 7, as the acid corrosion duration increased, the elastic modulus and peak stress gradually decreased while the strength degradation depth, ultimate strain, and peak strain enhanced drastically. It was because the chloride ion in the corrosion solution was diffused into the inside concrete to occur the replacement action with the Ca(OH)\(_2\) in the cement stone, resulting in a large number of gypsum and ettringite deposited and accumulated in the concrete pores. Meanwhile, the generated salt crystals contained a large amount of crystal water, forming the local expansion pressure in the pores of the concrete. Additionally, the deviation in the water-loss shrinkage deformation capacity between the cement mortar and coarse aggregate in concrete was obvious. Then, the stress concentration at the tip of the internal micro-crack occurred due to the uneven deformation between the cement mortar and coarse aggregate, which made the internal crack of concrete form and presented an obvious loose situation. Under the larger stress, micro-cracks in the concrete gradually expanded or even formed a penetrating crack, which was beneficial to more salt solution deposited into the concrete, and continued to accelerate the performance degradation of concrete. The internal damage to concrete became more obvious, and the strength of corrosion depth continuously enlarged as the acid corrosion duration increased. Accordingly, the peak stress and elastic modulus of the concrete showed an obvious decreasing trend. The deformation capacity of concrete materials increased significantly, and thus the ultimate strain and peak strain increased significantly due to the enhancement of the deformation capacity of concrete \cite{46}. However, to be noted, the peak strain was not the only important indicator reflecting the deformation capacity of concrete material.

It can also be seen from Figure 7 that the peak stress, peak strain, ultimate strain, and elastic modulus almost showed linear variation laws as the acid corrosion duration increased, and these values were determined by the equation \(d_{\text{wti}} = Pt + Z\), where \(d_{\text{wti}}\) represented the elastic modulus, peak stress, ultimate strain, and the peak strain of concrete under monotonic load, respectively, and \(t\) was the acid corrosion duration (d).
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noted, the peak strain was not the only important indicator reflecting the deformation capacity and strength of concrete reduced significantly for the specimen with an acid corrosion duration of 30 d.

Figure 7. Fitting relationship curves of mechanical properties for corroded concrete specimens under monotonic load: (a) elastic modulus; (b) peak stress; (c) peak strain; (d) ultimate strain.

In addition, the test results of each specimen under cyclic load are shown in Table 4, and they were calculated by using the same method as the monotonic load test. As can be seen in Table 4, as the acid corrosion duration increased, the peak stress of corroded concrete gradually decreased, but the peak strain and ultimate strain increased observably. The initial slope of the curve reduced rapidly, indicating that the elastic modulus gradually declined with the increase in corrosion duration. Compared with the uncorroded specimen, when the corrosion duration reached 30 d, the peak stress and elastic modulus decreased by 53.3% and 74.1%, respectively, whereas the peak strain and ultimate strain of concrete increased by 55.7% and 77.9%, respectively. Consequently, the compressive capacity and strength of concrete reduced significantly for the specimen with an acid corrosion duration of 30 d.

Table 4. Test results of each specimen under cyclic load.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Corrosion Duration/d</th>
<th>Peak Load/kN</th>
<th>Peak Displacement/mm</th>
<th>Ultimate Displacement/mm</th>
<th>Peak Stress/MPa</th>
<th>Peak Strain/$\times 10^{-6}$</th>
<th>Ultimate Strain/$\times 10^{-6}$</th>
<th>Elastic Modulus/$\times 10^4$ MPa</th>
<th>Strength Degradation Depth/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0-5</td>
<td>0</td>
<td>273.8</td>
<td>0.78</td>
<td>1.09</td>
<td>27.38</td>
<td>2607</td>
<td>3619</td>
<td>2.16</td>
<td>0</td>
</tr>
<tr>
<td>F1-6</td>
<td>6</td>
<td>246.2</td>
<td>0.83</td>
<td>1.28</td>
<td>25.62</td>
<td>2772</td>
<td>4273</td>
<td>1.96</td>
<td>2.13</td>
</tr>
<tr>
<td>F2-5</td>
<td>12</td>
<td>224.6</td>
<td>0.86</td>
<td>1.31</td>
<td>23.46</td>
<td>2871</td>
<td>4365</td>
<td>1.50</td>
<td>4.71</td>
</tr>
<tr>
<td>F3-5</td>
<td>18</td>
<td>209.8</td>
<td>0.91</td>
<td>1.44</td>
<td>20.98</td>
<td>3036</td>
<td>4786</td>
<td>1.26</td>
<td>6.23</td>
</tr>
<tr>
<td>F4-5</td>
<td>24</td>
<td>153.8</td>
<td>1.01</td>
<td>1.51</td>
<td>17.38</td>
<td>3366</td>
<td>5043</td>
<td>0.97</td>
<td>12.51</td>
</tr>
<tr>
<td>F5-4</td>
<td>30</td>
<td>128.2</td>
<td>1.22</td>
<td>1.93</td>
<td>12.80</td>
<td>4059</td>
<td>6437</td>
<td>0.56</td>
<td>16.24</td>
</tr>
</tbody>
</table>

Similarly, the variation trends of the elastic modulus, peak stress, peak strain, and ultimate strain of concrete specimens with different corrosion durations under cyclic...
loading are depicted in Figure 8. As can be seen in Figure 8, the elastic modulus, peak stress, peak strain, and ultimate strain essentially showed linear variation laws with the acid corrosion duration, and these values could be calculated by the equation $d_{citi} = Pt + Z$, where $d_{citi}$ was the elastic modulus, peak stress, ultimate strain and peak strain of concrete under cyclic load respectively, and $t$ represented the acid corrosion duration (d).

![Figure 8](image-url)

**Figure 8.** Fitting relationship curves of mechanical properties for corroded concrete specimens under cyclic load: (a) elastic modulus; (b) peak stress; (c) peak strain; (d) ultimate strain.

### 3.5. Damage Analysis of Corroded Concrete under Cyclic Load

The comparisons of stress–strain curves of concrete specimens with different acid corrosion durations under cyclic and monotonic loads are shown in Figure 9. As can be seen in Figure 9, the stress–strain envelope curves of acid corrosion concrete under cyclic and monotonic loads were essentially identical in the ascending section, and the deviations in peak stress between them were slight. However, for the descending section, the slope of the stress–strain curve of concrete under cyclic load was significantly less than that under monotonic load, and the descending section curves showed steep, and the stiffness degradation was obvious for the acid corrosion concrete under cyclic load. Compared with the monotonic load, the stiffness degradation rate of concrete under a large cyclic load enhanced significantly due to the internal damage accumulation of acid-corroded concrete. As a result, the corroded concrete exhibited an obvious brittleness characteristic, and the compressive strength declined rapidly.
In addition, the damage of corroded concrete specimens under cyclic load was accurately evaluated from three performance indicators, including residual deformation, damage variable, and accumulative energy dissipation.

1. Residual deformation

Figure 10 respective shows the relationship curves of the residual strain of concrete corroded by hydrochloric acid and strains at the unloading point and reloading point on the envelope curves.
where

$$x = (2)$$

Cumulative energy dissipation and damage variable ($D$) were shown in Equations (5) and (6):

$$\text{Equations (5) and (6):}$$

Relationship between the residual strain and unloading point strain was determined by

$$\text{Equations (3) and (4) as follows:}$$

$$x_p = 0.41x_a^2 + \alpha_a x_a$$

(3)

$$\alpha_a = 0.08\left(\frac{T}{100}\right)^2 + 0.37\left(\frac{T}{100}\right) + 0.0275$$

(4)

where $x_a$ represents the ratio of unloading point strain to peak strain ($\varepsilon_0$) on the envelope curve, and $x_p$ is the ratio of residual strain to peak strain ($\varepsilon_0$). $\alpha_a$ is a parameter related to the corrosion duration, and $T$ stands for the corrosion duration.

Similarly, normalized fitting was performed on the relationship curve in Figure 10b, and the relational equations between the residual strain of concrete and the corresponding reloading point strain at the unloading point on the envelope curve were shown in Equations (5) and (6):

$$x_p = 0.41x_b^2 + \alpha_b x_b$$

(5)

$$\alpha_b = 0.1\left(\frac{T}{100}\right)^2 + 0.4\left(\frac{T}{100}\right) + 0.0346$$

(6)

where $x_b$ is the ratio of the strain at the intersection of the loading curve and the envelope curve to peak strain ($\varepsilon_0$), and $\alpha_b$ represents a parameter related to the corrosion duration.

(2) Cumulative energy dissipation and damage variable ($D$)

The cumulative energy consumption ($E_{sum}$) was generally obtained by the area enclosed by the stress–strain curve of unit volume concrete. According to the definition of damage mechanics, damage variable ($D$) was defined as the loss rate of dynamic elastic modulus of concrete after acid corrosion, which was calculated by the following Equation (7):

$$D = \left|1 - \frac{E'}{E_0}\right|$$

(7)

where $D$ is the damage variable determined by the elastic modulus, $E_0$ is the elastic modulus of uncorroded concrete, and $E'$ represents the elastic modulus of corroded concrete.

The values of the damage variable ($D$) and cumulative energy dissipation ($E_{sum}$) for uncorroded and corroded concrete are shown in Table 5.
As can be seen in Table 5, the \( D \) value of concrete enlarged after corrosion and indicated the ductile damage degree gradually enhanced as the corrosion duration increased. In this case, the \( D \) value of concrete for the corrosion duration of 6 d was slight, demonstrating that the ductile damage of concrete has no obvious changes when the corrosion duration was less than 6 d. However, when the corrosion duration exceeded 12 d, the \( D \) value enhanced significantly with the increase in corrosion duration. As a result, the elastic modulus and compressive capacity of concrete declined notably due to the ductile damage severely of concrete. Meanwhile, as can also be seen in Table 5, the cumulative energy dissipation performance of concrete reduced slightly when the corrosion duration was less than 6 d, compared to uncorroded concrete. As the corrosion duration further increased, the cumulative energy dissipation reduced drastically, decreasing by 42.7%. Furthermore, for the concrete specimens with the corrosion duration of 24 d and 30 d, although the peak strain of concrete enlarged to some extent, the peak stress was reduced greatly compared to the uncorroded concrete. Therefore, the bearing capacity and the energy dissipation capacity of concrete specimens decreased significantly.

### 4. Constitutive Relationship of Corroded Concrete under Cyclic Load

#### 4.1. Effective Bearing Capacity Cross-Sectional Area Ratio

Due to the differences in acidic solution concentration, ambient temperature, and humidity in service environments of real structures and different tests, it was not accurate to evaluate the corrosion degree of concrete only using the corrosion duration. As a result, based on the strength degradation depth, the concept of effective bearing cross-sectional area ratio was proposed to characterize the corrosion degree of concrete, and the correction coefficient of descending section for the effective bearing cross-sectional area ratio was introduced to establish the stress–strain curve constitutive model of corroded concrete under cyclic load.

The effective bearing capacity cross-sectional area ratio \( p \) was defined as the proportion of the uncorroded layer area \( S_1 \) to the total area of the uncorroded concrete \( S_1 \) and corroded concrete layers \( S_1 \) (As seen in Figure 3), which was calculated by using Equation (8):

\[
p = \frac{S_1}{S_1 + S_2} = (1 - \frac{d_f}{a})^2
\]  

(8)

where \( S_1 \) and \( S_2 \) represent the section area of the uncorroded and corroded concrete layers, respectively. \( d_f \) represents the strength degradation depth of concrete, and \( a \) represents the side length of the concrete cross-section.

The measured strength degradation depth \( d_f \) and the effective bearing capacity cross-sectional area ratio \( p \) of all concrete specimens with different corrosion duration under cyclic load are shown in Figure 11. It can be seen from Figure 11 that the relationship curve between the strength degradation depth of concrete and the acid corrosion duration showed an exponential function. The strength degradation depth was calculated by using Equation (9).

\[
d_f = M + Ne^{Tx}
\]  

(9)
where $d_t$ represents the strength degradation depth of corroded concrete, and $T$ is the corrosion duration. $M$, $N$, and $m$ are constant parameters.

![Figure 11](image-url)

**Figure 11.** The variation laws of strength degradation depth and effective bearing capacity cross-sectional area ratio: (a) strength degradation depth; (b) effective bearing capacity cross-sectional area ratio.

Compared with the results proposed by [14,19,23], the strength degradation depth of hydrochloric acid corrosion concrete was slightly greater than that of the concrete corroded by sulfuric acid with the same corrosion duration. The reason was that at the initial stage of corrosion, sulfuric acid corrosion has a positive effect on the compressive strength of concrete, and the impact of hydrochloric acid corrosion on the strength degradation depth was essentially the same as that of sulfuric acid after the corrosion duration exceeded a certain number of days [19].

### 4.2. Model Establishment

To accurately assess the ascending section and descending sections of the stress–strain curve of acid-corroded concrete, the piecewise expression was used to fit the measured stress–strain curve of corroded concrete, which truly reflected the mechanical properties of concrete corroded by hydrochloric acid. In this section, the measured compression stress–strain curve of acid-corroded concrete under cyclic load was treated dimensionless by using the dimensionless method, and then the fitting formula of the stress–strain envelope curve was determined by the stress–strain relationship curve constitutive model proposed by Ding et al. [47,48], as shown in Equations (10)–(12).

$$
d_c = \begin{cases} 
\frac{Ax+(B-1)x^2}{1+(A-2)x+Bx^2} & x \leq 1 \\
\frac{x}{a_1(x-1)^2+x} & x > 1 
\end{cases}
$$

(10)

$$
d_c = \frac{\sigma}{f_c}
$$

(11)

$$
x = \frac{\epsilon}{\epsilon_c}
$$

(12)

where $\sigma$ and $\epsilon$ represent the stress and strain at any point of the stress–strain curve, and $f_c$ is the axial compressive strength. $\epsilon_c$ is the peak strain of concrete corresponding to the uniaxial compressive strength $f_c$, and $a_1$ is the parameter of the descending section of the stress–strain curve. $A$ stands for the ratio of the elastic modulus of concrete to the secant modulus of the peak point, and $B$ represents the parameter to control the attenuation degree of the elastic modulus for the ascending section curve.

Figure 12 shows the relationship curves between $A$, $B$, and the corrosion duration. Similarly, the relationship curves between $A$, $B$, and the effective bearing capacity cross-sectional area ratio $p$ are shown. As seen in Figure 12a, parameters $A$ and $B$ linearly
decreased with the increase in corrosion duration, and the reduced amplitude was lesser. This indicated that in the compressive stress state, the differences in the ascending section of stress-strain curves for the acid-corroded concrete under cyclic load and monotonic load were slight. Meanwhile, parameters A and B linearly also declined with the reduction of effective bearing capacity cross-sectional area ratio, as shown in Figure 12b.

**Figure 12.** Relationship curves between parameters A, B, and corrosion duration or effective bearing capacity cross-sectional area ratio \( p \): (a) relationship curve between A, B, and corrosion duration; (b) relationship curve between A, B, and \( 1-p \).

Compared Figure 9 with Figure 12, the ascending section of envelope curves for concrete under cyclic load and monotonic load were essentially coincident, indicating that the constitutive model proposed by [47] was reasonable and has good applicability to the ascending section of acid-corroded concrete. However, for the descending section of stress-strain curves, the deviations between concrete under cyclic load and monotonic load were more obvious, and the deviation significantly increased with the extension of corrosion duration. Therefore, for the descending section of stress-strain curves of acid-corroded concrete, the constitutive relationship of concrete [47] was no longer applicable. Moreover, the randomness properties of acid-corroded concrete were more significant, and thus the descending section of stress-strain curves for concrete under cyclic load became steeper than that of monotonic load since the accumulation of internal damage inside the concrete. To reflect this characteristic, the descending section of the stress-strain curves needs to be corrected, and the parameter correction coefficient \( \alpha_t \) of descending section related to the corrosion duration was proposed, as shown in Equations (13) and (14).

\[
\alpha_t = (0.158f_c^{0.783} - 0.913)\beta(D)
\]  

(13)

\[
\beta(D) = d^{\alpha_x+c} \frac{\alpha}{\alpha_c}
\]  

(14)

where \( \alpha_c \) represents the descending value of uncorroded concrete calculated by using the Chinese norm [45], and \( \alpha \) is a value determined according to the test \( \varepsilon_u/\varepsilon_c \), referred to [45]. Based on the analysis and calculation of the test results (Figure 13), the ratio \( \alpha \) is 2.574.
when the corrosion duration reached 30 d. Accordingly, the difference in descending section
of the stress–strain curve calculated by the Section 4.2 modified model was more conservative, compared with the experimental results. It was because the damage accumulation and deterioration of concrete under the combined coupled action of cyclic load and acid corrosion were more significant, the crack propagation was more irregular and unstable, and the randomness of severely acid-corroded concrete was stronger. Then, the acid-corroded severe concrete easier to suddenly suffer brittle failure after peak stress when the corrosion duration reached 30 d. Accordingly, the difference in descending section of the stress–strain curve between the results calculated by the proposed model and test values was nonnegligible for the concrete specimens when the corrosion duration reached 30 d, and the calculation results of Section 4.2 modified model were more conservative.

4.3. Model Verification

The constitutive relationship model of hydrochloric acid corrosion concrete established in Section 4.2 was used to calculate the stress–strain curves of acid-corroded concrete specimens under cyclic load, and the calculated results and test results are compared and depicted in Figure 14. As can be seen in Figure 14, the results calculated by Section 4.2 modified model matched well with the experimental results for concrete specimens with corrosion duration less than 24 d, which accurately reflected the stress–strain curve of acid-corroded concrete under cyclic load. However, for the concrete specimen with a corrosion duration of 30 d, the ascending section of the stress–strain curve calculated by the Section 4.2 modified model matched well with the experimental results for concrete specimens with corrosion duration less than 24 d, which accurately reflected the stress–strain curve of acid-corroded concrete under cyclic load. However, for the concrete specimen with a corrosion duration of 30 d, the ascending section of the stress–strain curve calculated by the Section 4.2 modified model was in good agreement with the test results, whereas the descending section has a certain deviation, and the results calculated by Section 4.2 proposed constitutive model were more conservative, compared with the experimental results. It was because the damage accumulation and deterioration of concrete under the combined coupled action of cyclic load and acid corrosion were more significant, the crack propagation was more irregular and unstable, and the randomness of severely acid-corroded concrete was stronger. Then, the acid-corroded severe concrete easier to suddenly suffer brittle failure after peak stress when the corrosion duration reached 30 d. Accordingly, the difference in descending section of the stress–strain curve between the results calculated by the proposed model and test values was nonnegligible for the concrete specimens when the corrosion duration reached 30 d, and the calculation results of Section 4.2 modified model were more conservative.

Figure 13. Correction coefficient of the constitutive relationship of acid-corroded concrete.

In addition, the unloading and reloading stress paths of acid-corroded concrete under cyclic compression load were determined by Equations (15) and (16).

\[
\sigma = E_r (\varepsilon - \varepsilon_p) \\
E_r = \frac{\sigma_{un}}{\varepsilon_{un} - \varepsilon_p}
\]

where \(\sigma\) and \(\varepsilon\) represent the compressive stress and compressive strain of acid-corroded concrete, respectively. \(\varepsilon_p\) is the residual strain of compressive concrete when unloading to zero stress point, and \(E_r\) is the deformation modulus of compressive concrete under unloading or reloading. \(\sigma_{un}\) and \(\varepsilon_{un}\) are the stress and strain of compressive concrete under unloading from the envelope curves.
This study has several limitations that may affect the results obtained. Firstly, in the test, more groups on specimens with different acid corrosion duration should be designed and prepared to further verify the experimental results and modeling constitutive relationship of hydrochloric acid corrosion concrete under cyclic compression loading. Meanwhile, the research object in the test was plain concrete; the influence of steel bar corrosion may be considered in the next work. In addition, due to the limitation of paper length, this paper mainly conducted experimental research and the establishment of a constitutive model of acid-corroded concrete and did not carry out finite element analysis [49,50]. It is a deficiency in our research that will be improved in future studies.
5. Conclusions

In this paper, six groups of concrete prism specimens with different hydrochloric acid corrosion duration were designed and constructed by the accelerated corrosion test method to investigate the influences of acid corrosion degree on the mechanical properties of concrete in an acid corrosion environment. Therefore, the monotonic load and cyclic load tests on these concrete prism specimens were carried out, and the failure modes, stress–strain curves, compressive strength, elastic modulus, peak strain, and ultimate strain of corroded concrete were measured and analyzed, compared to the uncorroded concrete. Meanwhile, based on the strength degradation depth, the concept of effective bearing cross-sectional area ratio was proposed to characterize the corrosion degree of concrete, and the correction coefficient of descending section for the effective bearing cross-sectional area ratio was introduced to establish the modified constitutive model of corroded concrete under cyclic load. The main conclusions can be drawn as follows:

(1) Hydrochloric acid corrosion has obvious effects on the failure characteristics of concrete. The surface of corroded concrete was easier to crack and crush under load. As the uniaxial compression load increased, several small cracks in the interior concrete and the vertical main cracks were obvious and continued to extend and widen, and thus the surface peeling area of the concrete enlarged. Meanwhile, the compressive capacity and ductility of concrete specimens reduced rapidly with the increase in corrosion duration.

(2) With the increase in corrosion duration, the strength degradation depth, peak strain, and ultimate strain of concrete under monotonic and cyclic loads increased significantly, whereas the peak stress and elastic modulus decreased drastically. The stress–strain curve of concrete after corrosion gradually changed flat with the extension of corrosion duration. Hydrochloric acid corrosion accelerated the degradation of the mechanical properties of concrete under load. The peak strain and ultimate strain of corroded concrete increased significantly when the corrosion duration reached 30 d and enhanced by 55.7% and 77.9% compared with the uncorroded concrete, whereas the peak stress and elastic modulus decreased rapidly and reduced by 53.3% and 74.1%, respectively.

(3) The stress–strain envelope curves for concrete with different corrosion duration under cyclic load were essentially similar to that of concrete under monotonic load. In this case, the slopes of ascending section for the stress–strain curves of corroded concrete under cyclic and monotonic loads were coincident. However, the deviations in the descending section curves between corroded concrete specimens under cyclic load and monotonic load were evident after the peak stress. The degradation rate of descending section for the stress–strain curve of corroded concrete under cyclic load was much larger than that of the monotonic load due to the accumulated internal damage of concrete.

(4) The modeling constitutive relationship of acid-corroded concrete under cyclic load was established, and the results calculated by this model matched well with the experimental values, indicating the model has a desirable fitting effect.

Meanwhile, steel bars are often cast together with concrete in practical engineering; further study on the performance degeneration of acid-corroded reinforced concrete members is a new direction for future research. Furthermore, how to better combine the finite element analysis method to achieve computational simulation analysis need to be further examined.

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References

2. Teymouri, M.; Behfarnia, K.; Shabani, A. Mix design effects on the durability of alkali-activated slag concrete in a hydrochloric acid environment. *Sustainability* 2021, 13, 8096. [CrossRef]
5. Liu, J.; Xie, C.; Fu, C.; Wei, X. Hydrochloric acid pretreatment of different types of rice husk ash influence on the properties of cement paste. *Materials* 2020, 13, 1524. [CrossRef] [PubMed]
6. Yunusa, M.; Zhang, X.; Cui, P. Durability of Recycled Concrete Aggregates Prepared with Mechanochemical and Thermal Treatment. *Materials* 2022, 15, 5792. [CrossRef] [PubMed]


