Review of corrosion test methods of prestressed anchor

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Abstract. Prestressed anchorage structures have been widely employed in water conservancy, hydropower, mining, transportation, and other industries as an essential reinforcement means in structures such as slope and underground cavities. The anchor corrosion during service caused widespread concern about the long-term durability of prestressed anchors. Corrosion tests, which can capture anchor corrosion initiation and development characteristics in various engineering environments, have gradually become an essential tool in the durability study of prestressed anchor structures. This study summarizes five commonly used testing methods for anchor corrosion and illustrates their applicability and defectiveness based on a comprehensive literature review and lessons learned from implementing anchor durability tests for prestressed anchors by several authors. This summary provides quick and practical guidance for those who will be studying anchor cable durability. Furthermore, the relevant literature is listed in this study for easy assessment by readers.

Introduction
Wide adoption of prestressed anchors in the fields of water conservancy and hydropower, mining, and transportation engineering has been demonstrated. Because the anchor cables’ metal structure is prone to corrosion, and the rock and soil media encountered are often corrosive, the anchor’s long-term durability has been a source of concern. The Fédération Internationale de la Précontrainte investigated 35 corroded anchoring structures and discovered the following: ① Anchor cable corrosion could occur in a little as 6 months and as long as 31 years. ② The damage occurred in 19 external anchor heads, 20 free sections of the cable body, and 2 internal anchor heads. ③ Permanent anchors fail 69% of the time, while temporary anchors fail 31% of the time [1,2]. The investigation shows that the corrosion of prestressed anchor cables occurs at a relatively random rate, with the corrosion of the free section of the anchor cable body and the outer anchor head receiving the most attention. Prestressed anchor cable corrosion failures have also been reported in the literature. For example, a prestressed anchor rod broke and shot out from the anchor hole at high speed in a hydropower station in northern Sweden after less than 30 years of operation [3,4]. In less than 2 years, a single-row prestressed anchor cable retaining wall broke several cables and flew away like a javelin [3,5]. After 14 years of service on a high-speed slope in Guangdong Province, the anchor cable’s outer anchor head still corroded severely under the protection of concrete. In a group of excavated anchor cables, two cable protection sleeves were seriously aged with severe rust in the cable body [6]. These failures demonstrate that the damage caused
by the corrosion of the anchor cable reduces the reliability of the anchoring structure and directly leads to the risk of casualties. Therefore, after the Third Scientific Research Institute of General Staff’s extensive onsite investigations and field tests, the term “time bomb” was coined to describe the severity of prestressed anchor cables failure [7,8]. A large number of prestressed anchor cables are currently being used in China’s civil engineering, water conservancy, and hydropower projects. According to incomplete statistics, the number of anchor cables used for the high slope of the three completed Gorges Ship Lock is 4376, with 130,000 anchor rods; the Baihetan Hydropower Station is currently under construction with 36,000 anchor cables and a large number of anchor rods of 3.8 million. All parties involved in anchor cable must respond to questions about the long-term durability of these prestressed anchor cables in use and how to evaluate their service performance [8].

In answering the above questions, it is necessary to clarify the corrosion mechanism of prestressed anchor cables, the law of corrosion development, and the corrosion damage mechanism on the anchoring structure. As a result, anchor cable corrosion tests are necessary and urgently needed. In addition, the test results can be used to support and verify research on the theory and method of evaluating the durability of prestressed anchor cables. Scholars have conducted numerous experimental studies on the anchor cable problems mentioned above using the various corrosion test methods and have achieved certain results [7-34]. Presently, there are two categories of corrosion tests for prestressed anchor cables: field and laboratory tests. This study summarizes several commonly used test methods in current research on the durability of prestressed anchor cables based on the summary and analysis of previous studies.

**Field test method**

Field tests are crucial in the study of prestressed anchor cables’ durability. The test data obtained through field tests can accurately reflect the actual service status of prestressed anchor cables. It is not only a test for existing anchor cables’ reasonable service life model. One of the most important performance criteria also serves as a vital link between other corrosion tests and reality. There are two ideas for onsite testing; one is “digging,” and the other is “embedding.” The corresponding two corrosion test methods are the onsite excavation and the onsite embedment tests.

![Field excavation test of prestressed service anchor cable in Manwan Hydropower Station](image-url)

**Figure 1**. Field excavation test of prestressed service anchor cable in Manwan Hydropower Station

**Onsite excavation test**

The use of blasting, digging, and other means to sample the prestressed anchors in service is referred to as an onsite excavation test (**Figure 1**). Ren, et al. [10] combined the onsite excavation test with indoor...
test methods, like acid pickling weight measurement, energy spectrum analysis, electrochemical (electrochemical) analysis of the causes of anchor cable corrosion, to describe the corrosion state of an anchor cable to evaluate the durability of the anchor cable. After digging a 20-year-old tension-focused full-length cohesive anchor cable on the left bank slope of Manwan Hydropower Station in 68 days, they discovered that cement mortar inclusions could protect the cable body. Furthermore, the mechanical properties and chemical composition of the anchor cables that have been in use for many years have remained relatively unchanged. Subsequently, Li, et al. [11,12] conducted field excavation tests and laboratory tests on the Shaping Hydropower Station’s three-year unbonded anchor cable. The stress anchor cable’s service state was also analyzed and evaluated. Wang, et al. [13,14] reported similar research and test methods for evaluating the service performance of the anchor cable in the Manwan Hydropower Station, Shaping Hydropower Station, Jinping Hydropower Station, and other projects.

In summary, the field excavation test provides the most accurate and reliable first-hand data and information on the corrosion status of the anchor cable during service; however, the excavation test itself is a labor- and material-intensive task that is difficult to perform on a large scale. There are currently few reports in the literature on on site excavation tests. As a result, the data obtained from the onsite excavation test is minimal and valuable.

![Figure 2](image-url)

**Figure 2.** Structure commonly used in the field embedment test of prestressed anchor cable

**Onsite embedment test**

To some extent, the onsite embedment test can be regarded as the field excavation optimization test. Bury the anchor cable sample in a hole near the actual service project of the prestressed anchor cable (Figure 2), take the sample out according to the set time of the test, and observe the corrosion morphology of the sample and calculate the corrosion rate. This test method has the advantage of making the sample environment more consistent with the actual anchor cable service environment and fully considers the feasibility and ease of sampling operation. Compared to the onsite excavation test, the difficulty of the test is significantly reduced, as is the cost of the workforce and material resources invested. Accordingly, the embedment test can be regarded as the optimization of the excavation test. By digging a hole near a reinforced slope and burying the anchor cable sample, Zheng, et al. [15] studied the influence of grouting defects on the corrosion rate of the anchor cable and established the prestressed anchor cable fracture under various corrosion conditions. The relationship curve between load and corrosion time enables predicting and evaluating the prestressed anchor cable’s service life. The test used strong corrosive soil instead of undisturbed soil to accelerate the corrosion, but the sample environment was closer to the actual service site, avoiding the influence of precipitation, temperature,
and other factors. At the same time, how to protect the test site from damage while conducting onsite embedment tests is also a key factor.

Coupon test [8] is another type of onsite embedment test. The coupon test is primarily used to study the outdoor atmosphere corrosion effect on metals. For anchor corrosion research, coupon test refers to drilling holes in the rock wall and placing samples in the holes. The holes of the rock wall are considered to restore the anchor’s actual environment.

Moreover, the Third Scientific Research Institute of General Staff [7,8] has conducted numerous research work in the early stage and has obtained rich results in the field investigation and test of the durability of anchor cables (rods), which will not be demonstrated in this study.

**Laboratory corrosion test method**

Although a field test can obtain real data on the corrosion of the prestressed anchor cable in service, the large-scale test is not feasible due to time and cost constraints. Furthermore, the single corrosion environment employed in the simulation by the field test makes it difficult to be generalized. On the other hand, the laboratory corrosion test has strong operability and good reproducibility. It can simulate the corrosion of prestressed anchor cables under a variety of influencing factors. Therefore, understanding these laboratory corrosion test methods is critical.

Research on the durability of prestressed anchor cables began late, and there are no established corrosion test standards or specifications for prestressed anchor cables. The current laboratory test research program is also based on conventional metal corrosion test standards or on learning from the reinforced concrete durability research experience. Except for the anchor cable material, it is difficult to directly apply the test method mentioned above because the prestressed anchor cable used in civil engineering is entirely different from the aforementioned structure and is difficult to directly detect when it is deeply buried in rock and soil. In addition to the material, we also need to pay attention to the particularity of the anchor cable structure. This section introduces and summarizes three examples of mainstream indoor test methods that can be used to study the durability of anchor cables: artificial climate method, infiltration test method, and electrolytic acceleration method.

**Artificial climate method**

The artificial climate method refers to the formation of a small artificial climate chamber through artificial control of temperature, humidity, and other influencing factors to accelerate the aging (corrosion) of materials. The artificial climate method is a widely used test method [16], mainly for evaluating the durability of building materials. The relevant standards have also been adjusted [17,18] in accordance with the different test objects. However, the current standard tests [16-18] emphasize the importance of artificial light sources (most common are the xenon lamps), which are primarily used to simulate the influence of natural light radiation on materials. The environment is relatively hidden for prestressed anchor cables (rods) or steel bars in concrete. As a result, the only factors that need to be controlled in studying this type of problem are humidity and temperature.

As Figure 3 shows, a simple artificial climate chamber would be a suitable option. The control system, air conditioning system, humidification system, and monitoring system make up the simple artificial climate room. The tester must set the temperature and humidity required for the test in the control system. The air conditioning, humidification, and monitoring systems will then begin to work with the monitoring system monitoring the changes in the environment’s temperature and humidity in real-time and feeds back to the control system. With the advancement of manufacturing technology, a small integrated simple artificial climate chamber can now be bought for about ¥25000 in the market. This product significantly reduces the test cost of the artificial climate method.
The artificial climate method was primarily employed to study the durability of reinforced concrete in the early stage [19-22]. Geng, et al. [19] explained the importance of the artificial climate method in the reinforced concrete durability study and introduced the idea of establishing a standard artificial climate accelerated degradation test. Using the artificial climate method, Dai, et al. [20] later studied the impact of different corrosion degrees of steel bars on the bond performance of concrete under cyclic loading conditions. In their study on the structural effects of accelerated corrosion of reinforced concrete beams, Yuan, et al. [21] introduced the artificial climate method and its test results in detail. Lu’s research on the durability of reinforced concrete structures under chloride salt corrosion environment also used and reported the artificial climate method [22]. The preceding studies all believe that the artificial climate method can better simulate the real-world corrosion of steel bars in concrete. In his Ph.D. thesis, Li [23] subsequently applied the artificial climate method to the durability study of steel strands and explored the stress corrosion problem of steel strands in concrete in the chloride environment. Liu [24] studied the corrosion characteristics of mortar-wrapped steel strands using the artificial climate method with controlled temperature and relative humidity. When studying the development of corrosion of steel bars in concrete under chloride salt conditions, Li, et al. [25] also used the artificial climate method and explored the influence of the stress level on the test results.

**Immersion corrosion test**

The immersion corrosion test has formed a relatively comprehensive standard and specification [26-28] widely used in various metals corrosion research. Based on the test piece’s relative position and the solution, it can be divided into full immersion and semi-immersion tests [9]. The immersion cycle is divided into a long-term immersion test (Figure 4a) and an alternate immersion test (Figure 4b).

![Figure 4](image_url)

**Figure 4. Diagram of the immersion test**
According to ASTM G31-12a [26], the preferred minimum ratio of a test solution volume to test specimen surface area is 0.20 mL/mm² (130 mL/in.²), and the test conditions should be controlled throughout the test to ensure reproducible results. For alternate immersion test, when there are no special requirements, the ratio of drying time to soaking time should be 5:1 according to ASTM G44-2013 and GB/T 19746-2018. Researchers in the field of corrosion [28-30] adopted the immersion test method as a mature test technique. This study mainly focuses on applying this method in the anchor cable corrosion study [12,32-34]. The long-term immersion test is considered to simulate the saturation of pore liquid in concrete, and the alternate immersion test is used to simulate atmospheric exposure. Li [12] studied the coupling relationship between the corrosion rate of steel strands and pH, chloride concentration, and duration based on the long-term infiltration corrosion test. Based on this method, Li [32] explored the corrosion laws of steel strands under the action of pH, duration, and stress. The test methods used in the studies above are long-term immersion test methods. The alternate immersion test method application in the study of anchor rope durability has not been reported. Carrying out this part of the work is required.

Electrolytic corrosion test

The electrolytic corrosion (EC) test accelerates corrosion by applying an electric current using the test metal as the anode and a particular inert metal as the cathode (Figure 5). Using the EC test to assess the corrosion resistance of the copper-nickel-chromium coating system is currently the most successful application of the electrolytic corrosion method [35,36]. Under the specified test conditions, the electrolytic method produces more consistent samples with the actual service. This method has also been incorporated into the international standard [35]. Secondly, the electrolytic accelerated corrosion test has been widely used as a common method to efficiently obtain samples with different corrosion rates in the corrosion research of steel bars [37-42]. In studying the effect of steel corrosion on the bond strength, Almusallam, et al. [37] used a 0.4 A constant current to obtain samples with different corrosion rates and established a calibration curve for the relationship between the duration of the applied current and the corresponding corrosion degree. The corrosion rate of steel bars was calibrated. Lee, et al. [38] and Fang, et al. [39,40] studied the corrosion degree of steel bars and the bond performance between concrete and steel bars using the same method. Fang, et al. [41] later studied the electrolytic accelerated corrosion law of steel bars in concrete with a 5% sodium chloride concentration and a current density of 9 mA/cm². Li, et al. [42] also used the electrolytic accelerated corrosion method in their recent study. Although the electrolysis method is well-established in the accelerated corrosion test of steel bars in concrete, it is less used in the related research of anchor cable corrosion [43]. The extensive use of the electrolytic method in studying steel corrosion problems can provide a reference for its application in the study of anchor rope durability.

![Figure 5](image-url) Diagram of the anchor cable electrolytic corrosion test for unstressed anchor cable (Yin, et al., 2021)

**Applicability and deficiencies of the above corrosion test methods**

Although the various corrosion test methods mentioned above provide technical means for studying anchor cable durability, their applications still have limitations and deficiencies. For example, while the field test method can provide convincing data on the anchor cable’s actual service status, it has drawbacks like a large workload and high test cost, and it is challenging to implement on a large scale.
Secondly, the anchor cable excavated on site has a relatively single service environment. It can only reflect the anchor cable corrosion in a specific environment, and the test result is not universal. Furthermore, protecting the anchor cable sample from “secondary oxidation” is one of the challenges during the onsite sampling process. When sampling, wrapping the anchor head with plastic wrap, cutting the excavated cable on time, and sealing the cable sample with a strip-plastic bag, can help avoid secondary oxidation to a certain extent.

The anchor cables can be studied under different atmospheric conditions using the artificial climate method. It is often used to explore the corrosion mechanism because the corrosion form of the anchor cable samples obtained by it is more consistent with the natural corrosion form of the anchor cables. The application of this method necessitates the establishment of a standard artificial climate chamber. At present, only China University of Mining and Technology, Hohai University, Zhejiang University, and other scientific research institutions have established a relatively complete artificial climate test system [23]. It will take some time to promote this method. Secondly, in a single test, the artificial climate method can only simulate one climatic condition. The time cost of using this method to explore the influence of temperature or humidity on corrosion is relatively high. When using this method to study the anchor cable’s durability, it is necessary to keep in mind the concealed particularity of the anchor cable service environment. The temperature and humidity selection should be thoroughly investigated and demonstrated.

As a standard metal corrosion test method, the test difficulty is in the container’s tightness during long-term infiltration and the oxygen content in the solution. Such problems were avoided in the current study on anchor cable infiltration corrosion. The oxygen content of the solution is limited when the container is closed. The corrosion reaction will gradually stop as the test time increases, which is inconsistent with the actual corrosion situation. Unless a unified standard on the oxygen issue is established, the test results’ reproducibility cannot be guaranteed. Therefore, the oxygen content changes in the solution should be monitored and recorded in real-time when using the infiltration method to study the corrosion characteristics of the anchor cable, and the oxygen content effect should be fully considered in the subsequent analysis of the test results.

Figure 6. Comparison of natural corrosion form and electrified corrosion form of reinforcement in concrete

In addition, the artificial climate and infiltration test methods generally have low corrosion efficiency problems. For example, Liu [24] used an artificial climate corrosion test to obtain most of the anchor cable samples after 4 months, and the corrosion rate was below 1%. This is relatively inefficient for conducting related or similar research on corrosion influence on the anchor cables’ mechanical properties. In contrast, the electrolysis method can efficiently and precisely obtain anchor cable samples with varying corrosion rates [43] and is often used to study the corrosion damage mechanism of the anchor cables.
anchoring system. However, the applicability of the electrolysis method in the study of the durability of steel bars or anchor cables is also debatable [21,23,43], with the focus primarily on two aspects of corrosion mechanism and corrosion form. First, the EC mechanism differs from the natural corrosion mechanism. Although both are electrochemical reactions, the latter is a galvanic reaction, whereas the former is an electrolytic reaction when connected to an external power supply. Secondly, when it comes to the corrosion of steel bars in concrete, there is a difference in the form of steel bars under natural and energized accelerated corrosion conditions. Steel bars corrode uniformly under energized conditions than they do naturally (Figure 6). Furthermore, there is a difference between the theoretically calculated corrosion and the experimentally measured corrosion amounts in the electrolytic test [37,39,41,43], and the reason for this is yet to be determined. The constant current electrolysis method can be considered when the corrosion rate of the anchor cable samples cannot be measured directly after the electrolysis test is completed, and the DC power supply should be checked and calibrated before the test. It is necessary to consider the limitations of the above method when selecting it. Based on literature research, the author combined and summarized the above five test methods commonly used in anchor cable corrosion research with their own experience and understanding of anchor cable durability study, as listed in Table 1.

| Category                  | Test method                     | Applicability                                                                 |
|---------------------------|---------------------------------|-------------------------------------------------------------------------------|
| Field corrosion test      | Onsite excavation test          | Evaluation of service performance of anchor cable, Establishment and test of life model of anchor cable, Corrosion mechanism of anchor cable |
|                           | Onsite embedment test           | Establishment of the life model of anchor cable, Exploration of the corrosion mechanism of anchor cable, Evaluation of cable durability |
|                           | Artificial climate method       | Exploration of corrosion mechanism of anchor cable, Establishment of the life model of anchor cable, Exploration of performance decay mechanism of an anchor structure, Establishment of durability evaluation of anchor cable |
| Laboratory corrosion test | Immersion corrosion test        | Exploration of corrosion mechanism of anchor cable, Establishment of the life model of anchor cable, Exploration of performance decay mechanism of an anchor structure, Establishment of durability evaluation of anchor cable |
|                           | Electrolytic corrosion test     | Rapid preparation of corrosion samples of anchor cable, Exploration of performance decay mechanism of an anchor structure, Establishment of durability evaluation of anchor cable |
Conclusion

Corrosion testing can intuitively understand the occurrence and development of corrosion of anchor cables in different environments and has gradually become an essential method for durability study. Based on numerous literature studies, this paper summarizes the five commonly used corrosion test methods in anchor cables’ field test and laboratory accelerated corrosion tests and outlines the applicability and deficiencies of various methods, which can be utilized for research on the durability of anchor cables.

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