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الحماية الكاثودية للهياكل الخرسانية المسلحة المتآكلة

CATHODIC PROTECTION OF CORRODED REINFORCED CONCRETE STRUCTURE

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الملخص:

لوحظت مشكلة التآكل في المباني الخرسانية المسلحة لأول مرة في ستينيات القرن الماضي، وازداد انتشارها بشكل ملحوظ منذ عام ١٩٧٥. يُشكل التآكل تحديًا كبيرًا في صيانة البنية التحتية، إذ يُسبب تلفًا وتدهورًا وحتى تدميرًا للهياكل الخرسانية. وإذا تُرك التآكل الشديد دون علاج، فقد يؤدي إلى أعطال غير متوقعة وإصلاحات مكلفة. ومنذ إدخال أنظمة الحماية الكاثودية في سبعينيات القرن الماضي، شهدت مكونات النظام وطرق الاختبار تطورات كبيرة. وتتوفر حاليًا تقنيات متنوعة لتقييم مدى وسرعة التآكل، بالإضافة إلى فعالية أنظمة الحماية الكاثودية. وفي حين أنه من المعترف به على نطاق واسع أن الحماية الكاثودية تُساعد في تخفيف تآكل حديد التسليح في الخرسانة، إلا أن التأثير الدقيق للتيار الكهربائي المار عبر الخرسانة لم يُفهم تمامًا بعد. وهناك حاجة حاليًا إلى تحقيق توازن بين تعقيدات الخرسانة والحماية الكاثودية، من أجل تطوير نظام حماية كاثودي بسيط وعملي. ويعالج استخدام الحماية الكاثودية (CP) الطبيعة الكهروكيميائية للتآكل ويوفر حماية من التآكل. ستوفر الدراسة تصميمًا وتفاصيل تقنيات تركيب نظام حماية كاثودية مُطبق على هيكل مصنوع من فولاذ متآكل.

الكلمات المفتاحية: الخرسانة، الفولاذ، الخرسانة المسلحة بالفولاذ، التآكل، الحماية الكاثودية.

Abstract:

The issue of corrosion in reinforced concrete buildings was first noted in the 1960s, and its prevalence has increased significantly since 1975. Corrosion poses a significant challenge in maintaining infrastructure, as it causes damage, deterioration, and even destruction of concrete structures. If left unchecked, severe corrosion can lead to unexpected failures and costly repairs, Since the introduction of cathodic protection systems in the 1970s, there have been significant advancements in system components and testing methods. Nowadays, various techniques are available to assess the extent and speed of corrosion, as well as the effectiveness of cathodic protection systems. While it is widely acknowledged that cathodic protection helps mitigate the corrosion of reinforcing steel in concrete, the exact impact of electric current passing through the concrete is not yet fully understood. Currently, there is a need to strike a balance between the complexities of concrete and cathodic protection, in order to develop a simple and functional cathodic protection system, The use of cathodic protection (CP) addresses the electrochemical nature of corrosion and provides corrosion protection. The study will provides the design and details of the installation techniques of a cathodic protection system applied to a structure with corroded steel.

Keywords: Concrete, steel, Steel Reinforced Concrete, Corrosion, Cathodic Protection.

Introduction

Reinforced concrete is widely used in constructing infrastructure, providing a secure environment for various activities and safeguarding people's belongings. The durability and stability of these structures are crucial factors. Concrete, with its high alkalinity (pH > 13.5), typically protects the reinforcing steel from corrosion. Even under such high alkalinity, the steel remains passivated and free from corrosion. Furthermore, a low water-to-cement ratio in well-compacted and properly cured concrete reduces the permeability of the steel surface to corrosive substances like chloride, carbon dioxide, and moisture. The high electrical resistivity of concrete hampers the flow of anodic to cathodic currents, further slowing down corrosion (Bertolini, 2012).

It is important to emphasize that in a well-designed, constructed, and maintained structure, there should be no concern regarding steel corrosion throughout its intended lifespan. Regrettably, achieving this desirable level of long-term endurance is often not realized in practice, leading to a significant increase in concrete reinforcement corrosion as a prevalent cause of degradation in many reinforced concrete structures in recent years.

Corrosion-related damages incur significant costs for governments, whether it be for restoration or reconstruction purposes. Numerous studies have focused on concrete deterioration and steel corrosion in concrete. By carefully monitoring structures for corrosion performance and implementing necessary adjustments in a timely manner, substantial savings can be achieved. Repairing corroded areas is a highly complex process that requires meticulous attention, and in most cases, the lifespan of the repair is limited.

On the other hand, corrosion monitoring offers a comprehensive understanding of a structure's condition over time. Remedial actions are typically taken when the structure's condition deteriorates significantly due to extensive corrosion of steel reinforcements, leading to concrete cracking and spalling. Many critical precast concrete structures have exhibited signs of distress within a short period, highlighting the importance of proactive corrosion monitoring.

Cathodic protection (CP) was initially introduced in the 1970s for reinforced structures, primarily focusing on bridge decks in the United States where de-icing salts were commonly used. Its applications expanded to include buildings, tunnels, marine structures, and substructures across the USA and Europe during the 1980s (Palmer, 2015). Before installing a CP system, any existing concrete damage must be repaired, although the extent of repair is typically less extensive compared to cases that require repair alone (Byrne, 2015). Cracked or spalling concrete areas are removed to allow superficial cleaning of the steel, followed by the application of a cementitious mortar. It is important to avoid the use of highly resistant polymer mortars and bonding agents in CP cases, as they can obstruct the flow of protection current (Polder, 2005). Overlays and repair mortars used in conjunction with CP systems should have similar electrical conductivity to the existing structure to ensure sufficient current flow. Surface preparation, often achieved through sand or water blasting, is performed on the continuous reinforcement to ensure comprehensive protection of the entire structure. The continuity of reinforcement is assessed through resistance measurements, and any gaps in reinforcement are addressed by creating slots in the concrete and welding bars between the reinforcement bars (Polder, 2005). Maintaining a minimum cover depth to the reinforcement is crucial to prevent short circuiting between the anode and cathodic steel.

Various methods can be employed to mitigate or address the effects of corrosion, including patch repair (Qian, Zhang, & Qu, 2006), surface treatments (Moan, 2005), electrochemical chloride migration, re-alkalization (for carbonated structures) (Wilson, Jawed, & Ngala, 2013), chemical impregnation with corrosion inhibitors, and cathodic protection (CP) (Yang et al., 2020). Several interconnected factors need to be considered when selecting repair techniques, such as weight restrictions, budget, the need for a monitoring system, maintenance requirements, traffic management during repairs, the extent and severity of damage, aesthetics, and technical limitations (Polder, 2020).

Patch repair is the most commonly used option, suitable for localized damage or when the impact of the damage is minimal. However, this method carries the risk of incipient anodes, which can lead to corrosion in the surrounding reinforcement areas. Surface treatments are typically employed as preventive measures or in combination with other techniques. Coatings act as physical barriers, preventing the ingress of chlorides and carbon dioxide. Both coatings and surface treatments are most effective when applied early, before corrosion of the reinforcement occurs. Impregnants, which are low-viscosity liquids, line the concrete pores to hinder ion migration. Corrosion inhibitors reduce the rate of metal dissolution, but their ability to completely halt or significantly reduce corrosion rates is still uncertain. They may provide additional protection against initial corrosion but are only suitable in specific circumstances (Polder, 2020).

Cathodic protection (CP) involves the use of an external anode to apply a small current to the reinforcement, forcing it to act as the cathode instead of the dissolving anode in an electrochemical cell. This method effectively controls corrosion over the entire treated area, reducing the need for extensive concrete repairs (Bahadori, 2014). Chloride extraction, on the other hand, is similar to CP but employs a significantly higher current density and is a one-time application. It involves drawing chloride ions out of the concrete towards the anode, where they are extracted into an electrolyte. This process also increases the concentration of protective hydroxyl ions. However, chloride extraction is only effective in the cover zone of concrete, removing approximately 70% of chloride ions from this area (Bahadori, 2014). It is not recommended for use with pre-stressed wires due to the increased risk of hydrogen embrittlement and the potential initiation of alkali aggregate reactions due to the elevated pH. Re-alkalization serves as an alternative to chloride extraction for carbonated concrete and is also a one-time treatment. It carries a lower risk of alkali aggregate reactions, although they can still occur in areas not affected by carbonation. Nonetheless, re-alkalization also has limitations when used with pre-stressed structures.

Cathodic protection (CP) is particularly effective in cases where corrosion is caused by chloride contamination (Broomfield, 2021). In CP, a current flows from an external anode to the reinforcement through the concrete, inducing a beneficial cathodic reaction at the steel surface and generating hydroxyl ions. The production of hydroxide ions raises the pH, promoting the migration of chloride ions away from the reinforcement and towards the anode at the concrete surface (Bloomstine, 2011).

Research on CP for reinforced concrete has focused on various aspects, including the materials and types of anodes used (Zhang, 2017), the development of novel monitoring systems (Guo et al., 2020), and the examination of current distribution within the reinforcement (Rowland, 2019). Studies have revealed that the majority of the current is concentrated on the reinforcement nearest to the surface, providing limited protection to deeper layers (Xu & Yao, 2009). Moreover, more severe corrosion rates often result in an uneven distribution of current (Byrne, Holmes, & Norton, 2016). Concretes with higher electrical resistances exhibit lower current distribution. However, in cases where current distribution is consistent, the high resistance of the surrounding concrete promotes the passivation of the steel (Tang, 2017). When incorporating anodic overlays, it is crucial to determine the optimal proportion of electrically conductive elements, such as graphite, to enhance conductivity without compromising the required mechanical properties (Ghods, 2010).

PROCEDUREs

Before making any decisions regarding repairs, an initial survey involving visual inspection was carried out to assess the extent of damage. Subsequently, a comprehensive investigation of the concrete was conducted to accurately determine the cause of deterioration and potential damages. The initial building inspection revealed significant defects, prompting the need for a thorough concrete investigation. This investigation encompassed various techniques such as visual examination, hammer tapping survey, covermeter survey, half-cell testing, carbonation depth assessment, inspection of steel reinforcement, analysis of cement/alkali content, and evaluation of chloride content. The investigation revealed evidence of concrete and steel damage, as well as corrosion-related issues, as depicted in Figures 1(a), (b), and (c).

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(a) (b) (c)

Fig. 1 Corroded Steel reinforcement (a) interior column, (b) exterior column, and (c) exterior column

In several areas of the columns, the corroded steel reinforcement exhibited an average corrosion level and loss of yield stress that amounted to approximately 30% of the steel area. Table 1 presents the average elongation loss, which was approximately 55%. Additionally, Table 2 illustrates the concentration of Cl- ions in the columns.

Table 1: Tension test of corroded steel rebar samples (1st floor)

Samples	Nominal Diameter (mm)	Actual Diameter (mm)	Actual Area (mm^2)	Yield Stress (N/mm^2)	Tensile Stress (N/mm^2)	Elongation%
Sound Steel	16	15.7	129	400	600	20 %
Corroded Steel	16	13.2	90	290	430	9%

Calculations are based on the nominal diameter

Table 2: Chemical analysis of concrete samples in RC columns as percentage of the cement weight

Sample Locations	Cl^- %
Ground Floor	2.75
1st Floor	0.67
2nd Floor	0.8
Limits of Egyptian Code	0.3

To assess the condition of the concrete in the defected columns, core samples were extracted, and the results are presented in Table 3. Visual inspection and hammer tapping survey identified areas of delamination, spalling, and exposed corroded reinforcement in both the columns and slab areas. The approximate percentage of delaminated surface area and spalling ranged from 5% to 30% in the columns, as indicated in Table 4.

Table 3: Compressive strength of the extracted core specimens

Sample Locations	Compressive strength, MPa
Ground Floor	23.6
2nd Floor	29.2

Table 4: Area of defected concrete

Sample Locations	Approximate Surface area spalling (%)
Ground Floor	5% to 30%
2nd Floor	5% to 20%

The covermeter survey results revealed an average cover depth of approximately 25 mm. The half-cell potential readings indicated a high risk of corrosion in several areas, as the readings were less than -350 mV (less negative) compared to the copper-copper sulphate half-cell electrode. The depth of carbonation measurements did not show significant signs of carbonation, with carbonated areas limited to the surface within a maximum depth of 5 mm.

Reinforcement inspection was conducted on all the affected columns, revealing moderate to severe pitting corrosion in several locations and slight to moderate general corrosion in other areas. Concrete samples were broken and tested to determine the cement and alkali content. The tests indicated that the alkali content was within normal limits.

Chloride content testing demonstrated extensive chloride contamination in all the columns, with values surpassing the threshold limit of 0.4% of the cement weight. The tested samples had depths ranging from 5 mm to 150 mm, which exceeded the depth of the steel reinforcement.

REPAIR PROCEDURE

After considering the extent of damage and the potential for further deterioration and structural failure caused by chloride penetration, it was evident that superficial solutions such as patch repair and concrete replacement would not be suitable. These methods would be unable to address the remaining chloride-contaminated areas, which could lead to accelerated steel corrosion next to the repaired sections due to the incipient anode effect. Additionally, the option of demolition and rebuilding was deemed costly.

Therefore, the chosen repair option was Cathodic Protection (CP), as it effectively prevents corrosion from recurring, even if some areas of the concrete remain contaminated. The CP system was tailored to the specific structure, and its installation was integrated with the concrete repair process. Practical considerations were thoroughly discussed to ensure a feasible and efficient repair work plan.

The work was carried out in two primary stages. The first stage focused on repairing the columns based on the level of corrosion present. The second stage involved implementing electrochemical protection measures.

During the repair stage, different approaches were employed depending on the extent of corrosion. For less corroded elements, the repair process involved sandblasting the reinforcing steel and restoring the concrete cover. Medium and highly corroded elements required more extensive repairs, such as the addition of new reinforcement and a concrete jacket. Figure 2 illustrates these repair methods.

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(a) (b)

Fig. 2 Sand blasted steel and new steel (a) interior column, (b) exterior column

During the second stage, a zinc mesh was installed on the surface of the columns, as depicted in Figures 3, 4, and 5. A strip was bent to extend outside the column. Over the zinc mesh, a 15 mm thick plaster layer was applied. An impressed current was then introduced, with the zinc leg connected to the positive pole and the stirrup leg connected to the negative pole of a DC power supply. Throughout the 7-day duration of current application, the column surfaces were kept moist. The potential difference of the current flow was monitored using a half-cell, as shown in Figure 6c.

The installation of the anodes began by removing all damaged concrete, including deteriorated areas around and behind the steel reinforcement of the columns, following established concrete repair practices. The exposed steel reinforcement was thoroughly cleaned through abrasive blasting until it achieved a bright condition. Continuous checks were performed to ensure a reliable electrical connection for all steel reinforcing. In cases where continuity was compromised, additional electrical connections were employed by drilling into sound reinforcing rebar in the relevant protective areas.

Steel rebars were incorporated into the concrete jacket, and the anode zinc mesh was installed on a grid pattern across the entire surface of the columns. The zinc mesh was connected to the steel reinforcement, and the electrical connection was verified using a multimeter. A cementitious repair mortar was then applied through shotcrete spraying. To house the connections and provide access for measuring current and voltage outputs, a watertight junction box was utilized, as depicted in Figure 3.

Monitoring of the system's performance was conducted through potential mapping at regular intervals, starting from weekly readings during the first two months and transitioning to monthly readings thereafter. The current output from the anodes ranged from 235 to 500 μA.

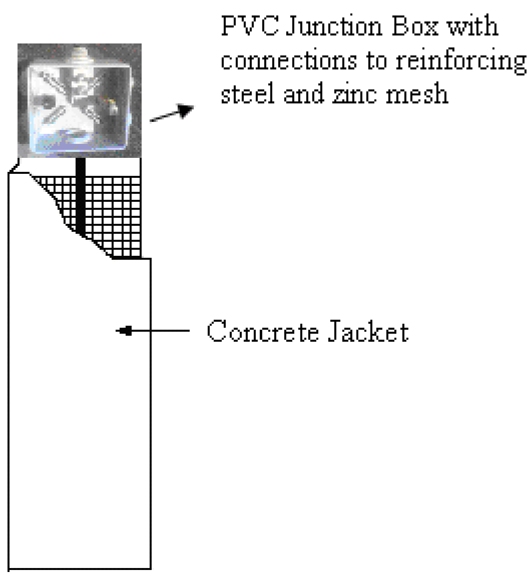

Fig. 3 Steel and zinc mesh for column repair

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Fig. 4 Grout Spraying using Shotcrete	**Fig. 5 Grouting and zinc mesh installation**

Following the period of impressed current flow, the steel leg was connected to the zinc strip leg within a junction box. The flow of current from zinc to the steel cage was examined under wet conditions, as illustrated in Figure 6.

(a)	(b)	(c)

Fig. 6 Electric current (a) current connection, (b) treated Column, (c) voltmeter readings

The repair system implemented was designed in accordance with the performance standards outlined in BS12696:2000. It involved the use of impressed current cathodic protection, which required a permanent DC power supply. The system incorporated a steel mesh and an anode system consisting of a zinc mesh.

The zinc mesh utilized in the repair system adhered to either ASTM A-190 expanded sheet or ASTM B69-01a for A190 alloy standards. It was connected to the steel reinforcement through a connection box, ensuring the necessary protective current was delivered to the steel.

The cathode current density applied to the steel was 20mA/m2. Each anode area was equipped with a negative cable connection to the reinforcement. The anode design current density was set at 110mA/m2, meeting the requirement for a 100mV potential shift specified in the NACE Standard RP 0290-90, which ensures effective cathodic protection.

The electrical continuity of the reinforcement was regularly tested in areas undergoing concrete repair. The anode system and cabling were securely fixed to the concrete substrate, and the effectiveness of the negative connections was verified.

By opting for sprayed concrete instead of the form-and-pour repair technique, the need for extensive formwork was reduced, resulting in quicker repair times. The dry spray technique, with water added at the nozzle, was employed for the application of the sprayed concrete overlay.

To ensure the continuity and integrity of the exposed parts of the steel mesh within the concrete, continuity testing was conducted. This involved measuring the inter-steel voltage using a high impedance voltmeter.

Monitoring of the cathodic protection (CP) system was performed regularly to confirm its proper functioning and operational status. During the initial two months, weekly monitoring was conducted. Following this period, verification tests were carried out every two months for a total duration of one year. These tests aimed to verify the effectiveness and performance of the CP system.

SERVICE LIFE

The service life of galvanic anodes is influenced by various factors, including zinc anode consumption and the impact of alkalinity reduction. According to certain studies, it is estimated that approximately 10% of the zinc in the anode is consumed over a 10-year period if the system remains in optimal condition, with a nominal current output of 60 mA.

This estimation is based on the assumption that the amount of lithium hydroxide monohydrate ($LiOH \bullet H_2O$) provided exceeds the amount consumed throughout the anode's lifespan. This ensures a consistently high pH value and a suitable alkaline level for the anode mortar.

To mitigate the effects of moisture and relative humidity (RH) on the anode's current output, the anode was encapsulated with a high alkalinity concrete mortar. This protective measure promotes and sustains the anodic activity of the zinc anode.

conclusions

The premature failure of concrete repairs or the degradation of surrounding concrete is a significant issue. This problem arises when the total chloride ion concentration in the concrete structure surpasses a critical threshold, leading to severe corrosion of the steel reinforcement.

To address this issue and protect the deteriorated structure affected by chloride contamination, a successful structural repair method was implemented. This repair method involved the application of a cathodic protection (CP) system, which incorporated both impressed current and the installation of a zinc mesh anode.

By utilizing the CP system, the damaged structure was safeguarded against corrosion caused by chloride contamination. This cathodic protection repair method is expected to prolong the service life of the building and mitigate future corrosion problems.

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