Chemical and electrochemical repair methods for the anchorage regions of grouted, post-tensioned concrete systems

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ABSTRACT

Grouted, post-tensioned concrete systems are commonly used for constructing bridges with an intended corrosion-free service life of 100+ years. However, the use of inadequate grout materials and improper grouting techniques have caused voids at the anchorage regions – resulting in premature corrosion (say, within one or two decades) of strands. In addition, re-grouting the voids with repair grout has aggravated the corrosion of strands at the interface between the base grout (usually carbonated) and repair grout due to the differences in their chemical properties – raising concerns and leading to reluctance in re-grouting the voids in tendons. This work focused on developing non-invasive chemical (re-alkalization) and electrochemical (galvanic cathodic protection) methods to repair the anchorages of grouted, post-tensioned concrete systems. Immersion experiments were conducted to assess the efficiency of alkaline solutions in re-alkalizing the carbonated grouts. It was found that 1 M $Ca(OH)_2$ solution can restore the pH of the carbonated grouts in about a day. Moreover, the electrochemical impedance spectroscopy studies indicated that 1 M $Ca(OH)_2$ solution can re-passivate the embedded strands within a week. It can be sometimes challenging to achieve complete re-alkalization and re-grouting of voids; hence, a redundant electrochemical system that could work from outside the anchorage was found necessary. Therefore, experiments were conducted to evaluate the viability of galvanic anodes in protecting the anchorages. It was found that a thin layer of grout surrounding the strand would be sufficient to provide ionic conductivity for the galvanic anode (connected to the strand-end outside the anchorage) to protect the strand portions inside the anchorage. Based on the study, recommendations for the repair of the anchorage regions using chemical and electrochemical methods are presented.

1. Introduction

Grouted, post-tensioned (PT) concrete systems are commonly used for constructing bridges with a target service life of 100+ years [1–3]. However, the use of inadequate grout materials and improper grouting techniques have caused voids at the anchorage regions – leading to premature corrosion (say, within one or two decades) of strands [1–5]. Plain cement grout (mixture of cement and water) and site-batched grout (mixture of cement, water, and expansive admixture) are still used as grouting material in many developing countries [6]. These grouts tend to bleed and segregate – resulting in the formation of bleedwater and associated voids at the anchorage region [1–8]. Typically, the anchorages should be protected by permanent anchorage protection caps, as shown in Fig. 1 [6]. The presence of voids and the absence of adequate anchorage protection can expose the prestressed steel and strand-grout-air (S-G-A) interface (exposed layer of grout) to humidity, rainwater, oxygen, carbon dioxide, and other deleterious elements. Fig. 2 shows the schematic of an inadequately grouted PT anchorage region with the bottom strands embedded inside the grout and the top strands exposed to the atmosphere. Such conditions could result in the contamination of the S-G-A interface with deleterious elements that can cause corrosion. Chlorides can cause pitting corrosion at the S-G-A interface when their concentration exceeds the chloride threshold of the prestressed steel-grout system [1,9]. Carbonation can reduce the pH of the S-G-A interface to less than 9, which can cause uniform corrosion of the prestressed steel strands [1]. If ignored, corrosion of strands can cause structural distress (reduction in the structural capacity) and could result in catastrophic failures [10–13]. The inset of Fig. 2 shows the photo of the outside region of an inadequately grouted anchorage exposing the strands. Also, the inset shows

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Fig. 1. Photo of a girder with permanent non-metallic anchorage caps [6].

another photo of the inside region of a corroded and failed tendon extracted from a 12-year-old bridge. Corrosion could be prevented by regular inspection and periodic maintenance. However, the major challenge is the inaccessibility of the tendons which are concealed within the duct and embedded inside the concrete (except for external PT concrete systems). It is nearly impossible to examine the condition of the strands from the outside. Hence, repair techniques focusing on the anchorages are found necessary. Re-grouting the voids with repair grout is a common method of repairing the anchorage region. However, this method can lead to accelerated galvanic corrosion at the interface between the base grout and repair grout due to differences in their chemical properties [14,15]. A tendon of a bridge in Virginia failed within four years after repair due to the incompatibility between the parent grout and the repair grout [16]. This problem has raised concerns

about re-grouting voids in tendons. Other repair techniques, such as chemical impregnation and cable de-humidification, may not be suitable for all field conditions as they require specialized equipment. In addition, the adopted repair strategy must prevent/protect the tendons from corrosion throughout the service life with limited intervention, which is a concern with the current repair methods. Hence, there is a dire need to formulate repair solutions that will completely protect the anchorage region (inside and outside the anchorage plate). Therefore, in this research, non-invasive chemical (re-alkalization) and electrochemical (galvanic cathodic protection) repair methods are developed, which can control the corrosion of anchorage regions and extend the service life of PT concrete systems by multiple decades.

The remaining paper is organized as follows: First, a review of the possible repair techniques and their challenges is presented. Then, experimental programs assessing the feasibility of re-alkalization and galvanic cathodic protection in protecting the anchorage regions of PT concrete systems are presented. Then, the procedure for the chemical and electrochemical repair of inadequately grouted PT anchorage regions is presented. Then, recommendations for the protection of newly constructed anchorages are presented.

1.1. Review of available repair techniques and their challenges

1.1.1. Re-grouting

Re-grouting the voids with repair grout is a commonly used method for repairing a PT system [17]. Extensive research has been conducted on the initial grouting of PT systems, which includes assessing the properties and optimizing the ingredients of the grout materials [3,4]. On the contrary, only limited literature is available on the re-grouting of PT tendons. Pre-packaged thixotrophic grouts with high bleed resistance must be used as repair grouts to fill the voids [5]. Also, it is important to ensure that the repair grout is chemically and electrochemically compatible with the parent grout before the application [14,18]. However, it could be challenging to completely fill the voids in the duct [19,
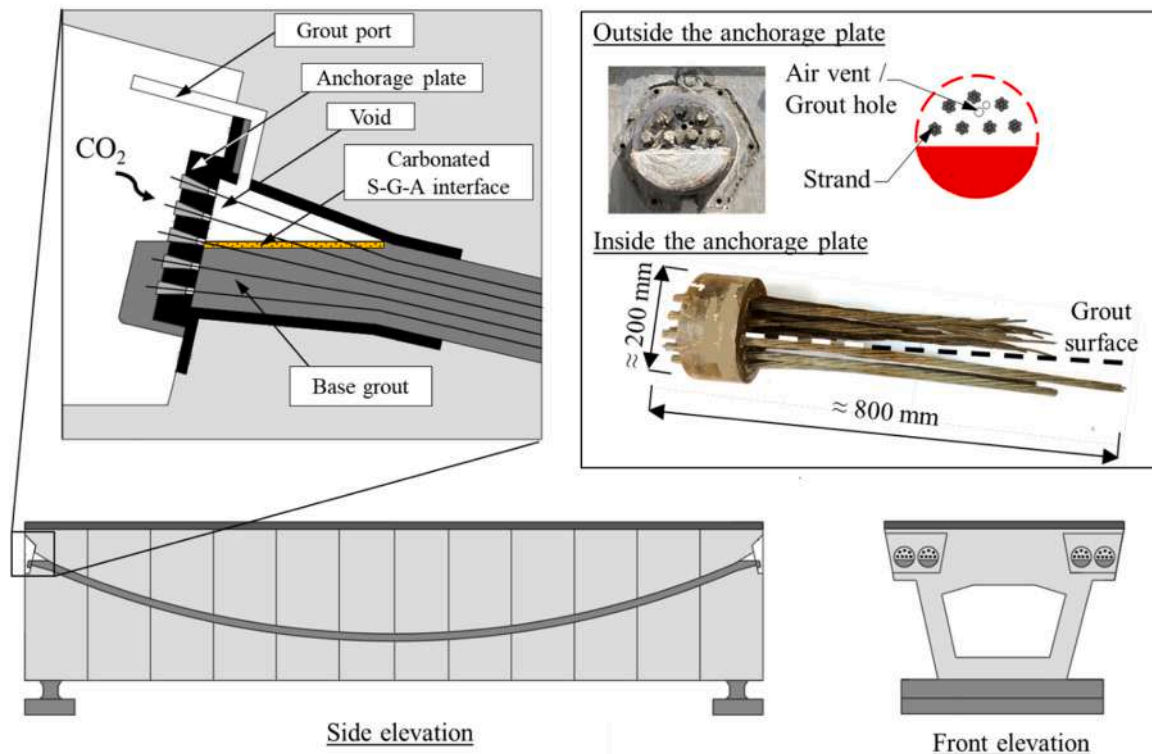

Fig. 2. Schematic of a post-tensioned concrete bridge with inadequately grouted anchorage (Inset: Photos and schematic of the outside and inside region of an inadequately grouted anchorage).

20].

1.1.2. Chemical impregnation

Chemical impregnation is gaining widespread importance, in which, silicon and hydrocarbon-based chemicals are impregnated through the interstitial spaces in the strands under pressure. These chemicals will form a thin film around the steel and improve its corrosion resistance by inhibiting the cathodic and anodic sites [21]. In addition, it is also recommended to inject neutral-pH rust-removing solutions along with the corrosion-inhibiting chemicals. The rust-removing solutions will remove the rust from the steel surface by the process of selective chelation [20]. However, it could be difficult to inject the chemicals into PT systems with impervious grouts [21,22].

1.1.3. Cable drying/De-humidification

Cable drying/De-humidification is a technique in which inert non-corrosive gases, such as nitrogen, can be pumped into the ducts under pressure (12 to 15 psi) [23]. These gases can displace the oxygen available inside the duct and reduce the humidity of the grout (< 40 %), which can inhibit the corrosion. However, it could be difficult to maintain the required pressure, especially for highly impervious grouts [20]. Also, the application of this method is still in the developmental stage.

1.1.4. Re-alkalization

The authors could not find any literature reporting the re-alkalization of carbonated grouts in PT systems. However, a few literature are available on the re-alkalization of carbonated concrete [24–33]. Carbonated concrete can be re-alkalized by short-term treatments such as i) Capillary absorption of highly alkaline solutions, ii) Electrochemical re-alkalization (ERA), and iii) Chemical treatment. Re-alkalization can increase the alkalinity of carbonated regions to 12 and above and does not require replacing the carbonated regions [24]. The alkalinity of the carbonated region can be restored by the capillary absorption of an alkaline solution having a pH greater than 12 into the pores of the concrete [24]. Low viscous alkaline solutions like sodium bicarbonate, sodium carbonate, potassium carbonate, calcium hydroxide, sodium phosphate, sodium hydroxide, lithium hydroxide, and lithium carbonate can be used [25–27]. The rate of penetration of the alkaline solution depends on the moisture content of the pores (The drier the condition, the greater the absorption will be) [28]. Re-alkalization by the absorption and diffusion of the alkaline solution has received less attention in the scientific literature. The re-alkalized specimens would not easily re-carbonate, and their resistance to further carbonation depends on i) the alkalinity of the absorbed solution, ii) the amount of solution absorbed, and iii) the buffering ability of the absorbed solution [29]. In ERA, the alkalinity is restored by applying a temporary cathodic current (usually 1 to 2 A/m^2 of steel area or applied voltage of 10 to 40 V) to the steel in the presence of a high alkaline electrolyte solution [30]. The alkaline solutions can be sodium bicarbonate or sodium carbonate [30,31]. During ERA, hydroxyl ions are generated at the steel surface due to the cathodic reaction. Also, there will be movement of the alkaline solution from the cover region of the concrete element towards the steel because of electroosmosis, electrophoresis, electromigration, diffusion, and/or capillary absorption [28, 32]. There could be a problem with the ERA due to the susceptibility of hydrogen-assisted environmental cracking of prestressed strands due to the passage of high currents [33]. In addition to the above methods, the alkalinity of a carbonated element can be restored by migration-type corrosion inhibitors containing chemicals such as hydroxides, nitrites, and phosphates [24].

1.1.5. Cathodic protection

Cathodic protection (CP) is an electrochemical process that involves the polarization of steel (metal to be protected) towards the cathodic region. The principle of CP is to supply electrons from a sacrificial metal (called galvanic cathodic protection) or with the help of a direct external current source (called Impressed current cathodic protection) [34]. By supplying charge, the potential of the steel is forced towards the range of passivity, or the macro-couple activity on the steel surface is reduced [34,35]. The protection is also achieved by the generation of hydroxyl ions due to the cathodic reaction around the steel surface, leading to the re-alkalization of the surrounding concrete [36,37].

CP of prestressed steel is mainly used in prestressed concrete cylinder pipes used for the transmission of sewer and water [38]. In prestressed concrete bridges, CP is mainly used to protect the mild steel reinforcements from corrosion [39]. However, applying CP to the prestressed strand is still in the developmental stage due to concerns such as hydrogen embrittlement (HE). HE is a phenomenon that can occur when the steel is over-polarised in the cathodic direction, which can cause brittle failures [40]. However, galvanic anodes may not cause HE due to their limited polarization effect and the high ohmic losses due to the highly resistive concrete [41]. In addition, other concerns such as barrier effect from metallic/plastic ducts and stray current corrosion when proper electrical continuity is not achieved must also be taken into account.

2. Research significance

A huge inventory of PT concrete bridges is being built in many developing nations as a result of the construction boom. However, many such bridges are inadequately grouted and could be on the verge of corrosion and associated structural distress. These bridges are important assets for a country, and the failure or de-commissioning of such bridges would impact the safety of the people and economy of the country. Hence, the construction industry can face a huge challenge in repairing and maintaining these inadequately grouted PT bridges. This paper proposes non-invasive, chemical and electrochemical methods to control corrosion of anchorages and extend the service life of PT concrete bridges. The proposed repair methods are very simple, less time-consuming, and do not require any specialized equipment for the application. The recommendations from this research will be crucial in helping decision-makers and repair engineers to develop, plan, and budget repair strategies that will ensure a target service life of 100+ years for PT concrete bridges.

3. Experimental methods and materials

The experimental program involves (i) assessing the re-alkalization and re-passivation efficiency of two alkaline solutions (1 M Ca(OH)$_2$ and 1 M Na$_2$CO$_3$) and (ii) assessing the feasibility of galvanic anodes in protecting the strands inside the anchorage plate. The grouts used in this study were (i) plain cement grout (PCG), which had a water/binder ratio of 0.44, and (ii) site-batched grout (SBG), which had a water/binder ratio of 0.45 and plasticized expansive admixture dosage of 0.45 % by weight of the binder. PCG and SBG were selected for this study because they were/are still used for PT tendon grouting applications in many developing nations. Before designing the experiments for the re-alkalization study, it was important to understand the expected depth of carbonation for grouts in PT bridges, which is presented next.

3.1. Expected depth of carbonation of grouts in PT bridges

Prisms (25 × 25 × 285 mm) were cast with PCG and SBG. The specimens were demoulded after 24 h and were coated with three layers of epoxy on all faces except the top face to facilitate one-dimensional CO$_2$ penetration. The specimens were not cured to represent the field condition. After about one day of hardening of epoxy, the specimens were exposed to a Natural – Sheltered exposure on a rooftop in Chennai, India. This condition represents moderate humidity (XC3 class) and cyclic wet and dry (XC4 class) conditions as per EN 206 [42]. The carbonation depth was measured at regular intervals by spraying a
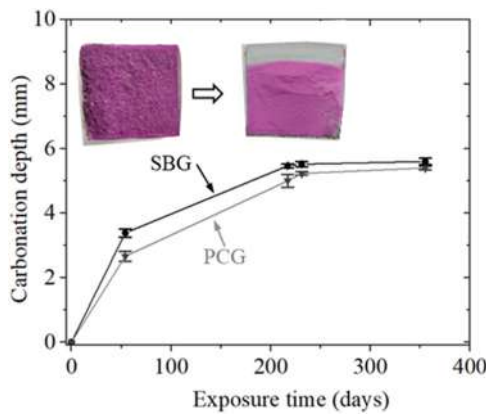
Fig. 3. Carbonation depth profile of grouts exposed to a Natural – Sheltered environment.

phenolphthalein indicator on the freshly broken surface of the specimen. The colourless region indicates the carbonated region, and the pink region indicates the pristine region. Fig. 3 shows the carbonation depth profile of PCG and SBG. A carbonation depth of ≈ 5 and ≈ 6 mm was seen for PCG and SBG, respectively, after approximately a year of exposure. It was inferred that the rate of increase in carbonation would be slow after this point, and hence, the exposure was stopped. A study reported that the grout used in the ducts of the Mid Bay Bridge in Florida has carbonated to a depth of ≈ 6 mm after 17 years [1]. Based on the literature and the present investigation, it was assumed that grouts (PCG and SBG) could carbonate to a depth of 5 to 10 mm and after that, the increase in depth will not be significant. Hence, specimens with a carbonation depth of 10 mm were used in the re-alkalization studies.

3.2. Re-alkalization using absorption of alkaline solutions

Prisms ($25 \times 25 \times 285$ mm), with PCG and SBG, were prepared according to the procedure outlined in Section 3.1 and exposed to accelerated CO_2 conditions (≈ 3 % CO_2, 65 ± 2 % RH, and 25 ± 2 °C) in an environmental chamber. These conditions were selected based on IS 516 (Part 2/Section 4): 2021 [43], which specifies the procedure for evaluating the carbonation resistance of concrete using an accelerated carbonation test. The carbonation depth was regularly measured using a phenolphthalein indicator. The exposure was stopped when the specimens had partially carbonated (≈ 10 mm). The procedure for re-alkalizing the partially carbonated grouts is shown in Fig. 4. First, the specimens were completely immersed in a tray containing an alkaline solution, with the uncoated surface of the specimen facing the top to facilitate the diffusion of the solution, as shown in Fig. 5. Two alkaline solutions were used, i) 1 M $Ca(OH)_2$ with a pH of ≈ 12.4 and ii) 1 M Na_2CO_3 with a pH of ≈ 11.5 These chemicals were chosen because of

their high pH and buffering abilities. The concentrations were selected based on the solubility limits of the chemicals and to provide sufficient buffer capacity to the solutions. The re-alkalization front was measured regularly using the phenolphthalein indicator. Additionally, chunks of samples were collected from the re-alkalized region, and the pH was measured using a pH electrode.

Another study was conducted to determine the duration required for re-alkalization. For this, the mass of the partially carbonated specimens was measured initially, and the specimens were immersed in the alkaline solutions. After 24 h, the specimens were removed from the tray, wiped with a clean cotton cloth, and allowed to dry for about 2 min. The mass of the specimens was measured, and the percentage absorption was calculated. Then, the specimens were immersed back into the solution. The above procedure was repeated every day till the specimens have fully reached their absorption capacity (change in the mass becomes less than 0.1 %). In addition to restoring the pH of the carbonated grout, the alkaline solution could aid in re-passivating the steel strands in contact with the solution and is presented next.

3.3. Re-passivation of prestressing steel

The ability of the alkaline solutions to re-passivate the prestressing

Fig. 5. Photos showing partially carbonated grout specimens immersed in 1 M $Ca(OH)_2$ (shown on the left)and 1 M Na_2CO_3 (shown on the right) solutions.
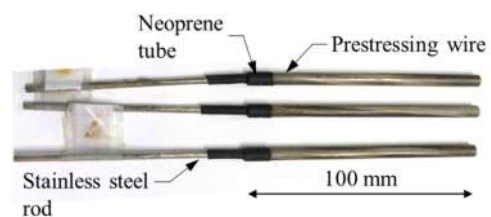

Fig. 6. Photo of the prestressing wire specimens used to assess the re-passivating ability of the alkaline solutions.
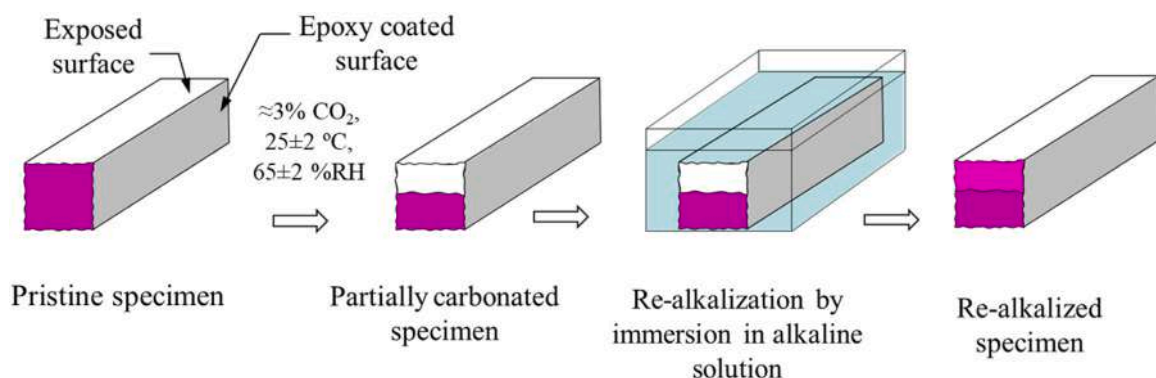

Fig. 4. Schematic of steps involved in the re-alkalization of carbonated grouts.
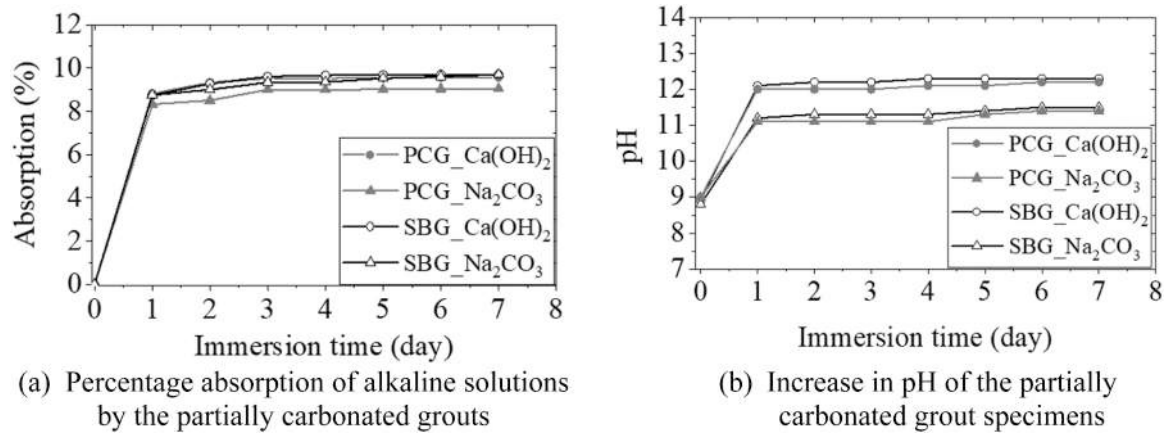
Fig. 7. Percentage absorption of alkaline solutions and the increase in pH after re-alkalization.

steel was assessed by conducting a steel-solution study with the help of Electrochemical Impedance Spectroscopy (EIS). The central king-wire of 5.2 mm diameter, extracted from a 15.2 mm diameter strand, was used as the test specimen, as shown in Fig. 6. A stainless steel rod of 3 mm diameter was fastened to the prestressing steel at one end for EIS measurements. The junction between the prestressing steel and the stainless steel rod was sealed using a neoprene tube. Two sets of specimens (three in each set), were immersed in 1 M Ca(OH)$_2$ and 1 M Na$_2$CO$_3$ solutions, respectively. The electrolytes used for EIS testing were the same immersion solutions. Nichrome mesh was used as the counter electrode and a saturated calomel electrode was used as the reference electrode. EIS testing was conducted on the specimens at regular intervals with a frequency range of 0.01 to 10^6 Hz with 10 mV amplitude. Re-alkalization of the carbonated S-G-A interface and complete re-grouting of voids can sometimes be challenging. Therefore, a redundant electrochemical repair system that can work without the complete filling of voids and be implemented from outside the tendon anchorage was found necessary and is presented in the following section.

3.4. Cathodic protection of post-tensioned anchorages

This paper proposes the connection of a galvanic anode to the strand end outside the anchorage, with the expectation that the anode would protect the strands within the anchorage, as well as the strands and other metallic components outside of it. Tests were carried out with specimens mimicking the anchorage region to determine whether a galvanic anode attached to the strand-end outside the tendon anchorage could protect the strand region inside the anchorage from corrosion. The specifics of the experiments, as well as the results and conclusions drawn from them, are presented in Section 4.3.

4. Results and discussions

4.1. Re-alkalization using absorption of alkaline solutions

Fig. 7 shows the percentage absorption of the alkaline solution by the partially carbonated grout specimens. The percentage absorption was calculated by measuring the difference in the mass of the specimen before and after immersion and dividing it by the initial mass. It was observed that after one day of immersion, there was a sudden increase in the mass of the specimens (for both PCG and SBG). The increase in mass is due to the absorption of the solution into the specimen. Then, the specimens were immersed again into the alkaline solutions, and the measurement was repeated every day for about one week. The results indicate that the percentage increase in absorption was not significant after one day. It can be inferred that the solution could saturate the specimens completely within one day of immersion.

Fig. 8 shows the photo of the broken surface of the partially carbonated and re-alkalized specimens immersed in 1 M Ca(OH)$_2$ solution (after 1 day of immersion) after spraying the phenolphthalein indicator. In the re-alkalized specimen, two shades (light pink and dark pink) can be observed. The dark pink region indicates the pristine region, and the light pink region is the re-alkalized region. The pH of the carbonated region of PCG and SBG before immersion was around 9. After one day, the pH of PCG immersed in 1 M CaOH$_2$ and 1 M Na$_2$CO$_3$ increased to 12.1 and 11.3, respectively. Similarly, the pH of SBG immersed in 1 M CaOH$_2$ and 1 M Na$_2$CO$_3$ increased to 12.4 and 11.5, respectively. It can be concluded that 1 M Ca(OH)$_2$ was effective in restoring the pH of the carbonated grouts. However, the main advantage of using 1 M Na$_2$CO$_3$ solution is its resistance to re-carbonation because of the absence of the hydroxyl group in its composition. However, in practice, the repair of PT anchorage involves re-alkalizing the
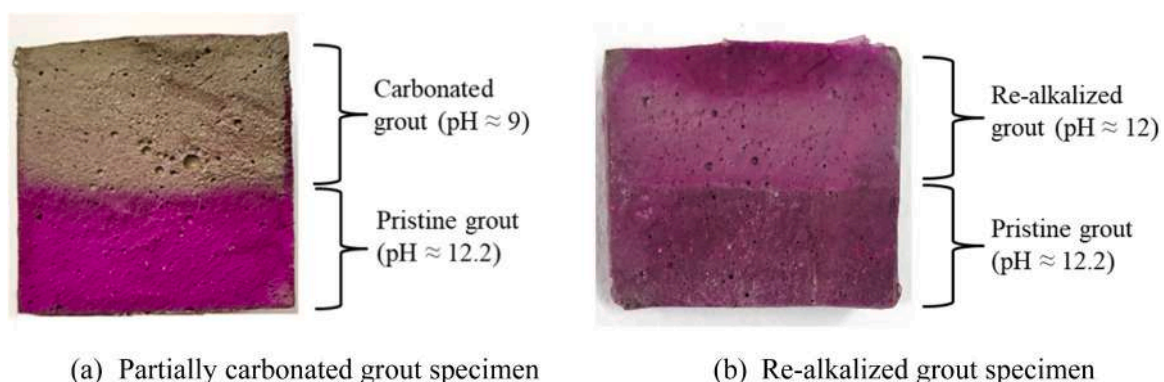

Fig. 8. Photos of the grout specimen before and after re-alkalization in 1 M Ca(OH)$_2$ solution (photo taken after one day of immersion).
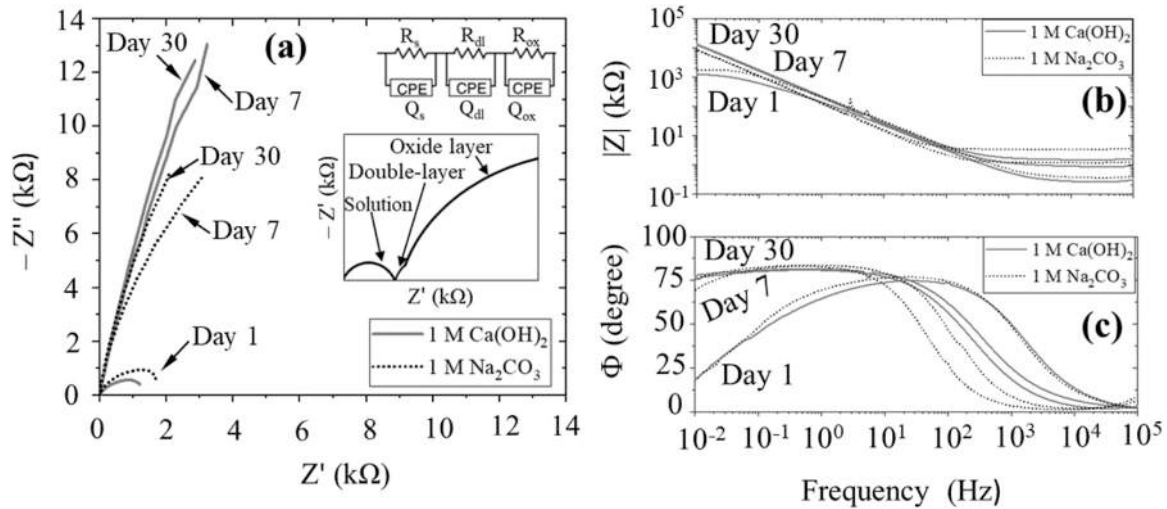
Fig. 9. EIS responses obtained from the specimens immersed in alkaline solutions (a) Nyquist (b) Bode magnitude, and (c) Bode phase formats.

carbonated interface followed by re-grouting the voids. Therefore, there are no possibilities for further carbonation. Hence, this study recommends the use of 1 M Ca(OH)$_2$ solution for restoring the pH of the carbonated grouts. In addition, the effect of the solutions on the re-passivation of the prestressing steel has to be considered, which is presented next.

4.2. Re-passivation of prestressing steel

During the process of corrosion, the surface layer of a metal gets converted into various forms of metal oxides. This transformation involves the reduction in the polarization resistance (which can be synonymously called Impedance) of the surface oxide layer of the metal. This reduction in the impedance of the oxide layer can be captured using the EIS technique. During the process of re-alkalization, the alkaline solutions, due to their high pH increase the impedance of the oxide layer of the metal. Fig. 9 shows the Nyquist response of prestressing wire specimens immersed in 1 M Ca(OH)$_2$ and 1 M Na$_2$CO$_3$ solutions. The x-axis and y-axis of Fig. 9(a) represent the real and imaginary part of the impedance, respectively. In Fig. 9(a), three incomplete semicircles are observed and are found overlapping. The magnitude (diameter) of the first two semicircles is very small and is not clearly visible in the figure. The analysis is based on the shape of the third semicircle which is clearly visible in the figure. A schematic of a typical EIS response is added as an inset in Fig. 9(a) for easy and clear understanding of the readers. To model the response from the specimens, a three resistor (R) – constant phase element (Q) circuit was used, as shown in the inset of Fig. 9(a). The response from the solution (R$_s$ and Q$_s$) is represented by the first semicircle, while the double layer (R$_{dl}$ and Q$_{dl}$) is represented by the second semicircle. The response from the oxide layer of the prestressing steel (R$_{ox}$ and Q$_{ox}$), is represented by the third semicircle. The re-passivation of the specimens was assessed by comparing the oxide layer characteristic (R$_{ox}$) before and after immersion in the solutions. The state of the passive layer is qualitatively indicated by the slope of the arc in the low frequency (10^{-1} to 10^{-2} Hz) area of the Nyquist representation. A steeper slope indicates a semicircle with a larger diameter, indicating a larger R$_{ox}$. Pre-corroded prestressing wire specimens were immersed in alkaline solutions, and the EIS response on Day 1 revealed a smaller slope in the low frequency area. A smaller slope signifies a smaller R$_{ox}$ and represents an actively corroding system. The specimens were left immersed in the solution, and EIS testing was conducted on Day 7 and Day 30. It was observed that the slope in the low frequency region increased to over 45°. This qualitatively confirms an improvement in oxide layer resistance and signifies the re-passivation of the
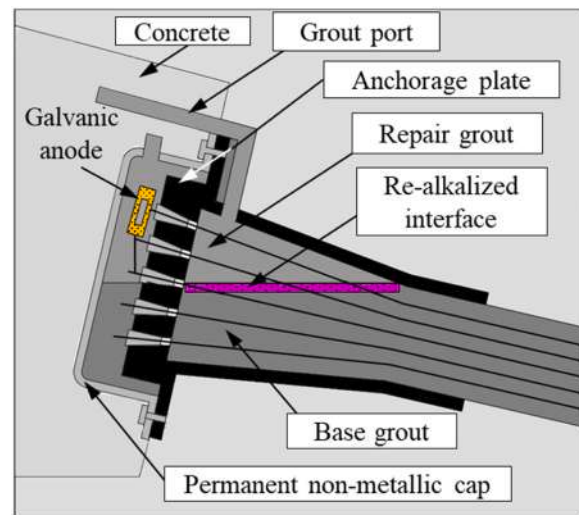

Fig. 10. Schematic of a post-tensioned anchorage region protected by a galvanic anode.

specimens. This can be inferred from the Bode frequency and magnitude responses. A progressive increase in magnitude and phase angle corresponding to the low frequency region (0.01 Hz) suggests a change in the oxide layer characteristic. The $|Z|_{0.01}$ increased from 1.8 kΩ on Day 7 to 12 kΩ on Day 30 for specimens immersed in 1 M Ca(OH)$_2$ solution. The $\varphi_{0.01}$ also increased from 20 to 75 degrees. Similarly, the $|Z|_{0.01}$ increased from 2 kΩ on Day 7 to 8 kΩ on Day 30 for specimens immersed in 1 M Na$_2$CO$_3$ solution. The $\varphi_{0.01}$ also increased from 20 to 70 degrees. These results confirm that the specimens were re-passivated. The EIS data indicates that the 1 M Ca(OH)$_2$ solution is more effective in re-passivating the steel compared to the 1 M Na$_2$CO$_3$ solution. The high pH (12.4) of the 1 M Ca(OH)$_2$ solution should have enabled its high re-passivating ability.

4.3. Cathodic protection of post-tensioned anchorages

Fig. 10 shows the schematic of a PT anchorage region, where a galvanic anode was connected to the strand outside the anchorage. A galvanic anode requires an ionic path (provided by the grout) for the transfer of ions and an electronic path (provided by the prestressed strand) for the transfer of electrons. It can be visualized from Fig. 10 that
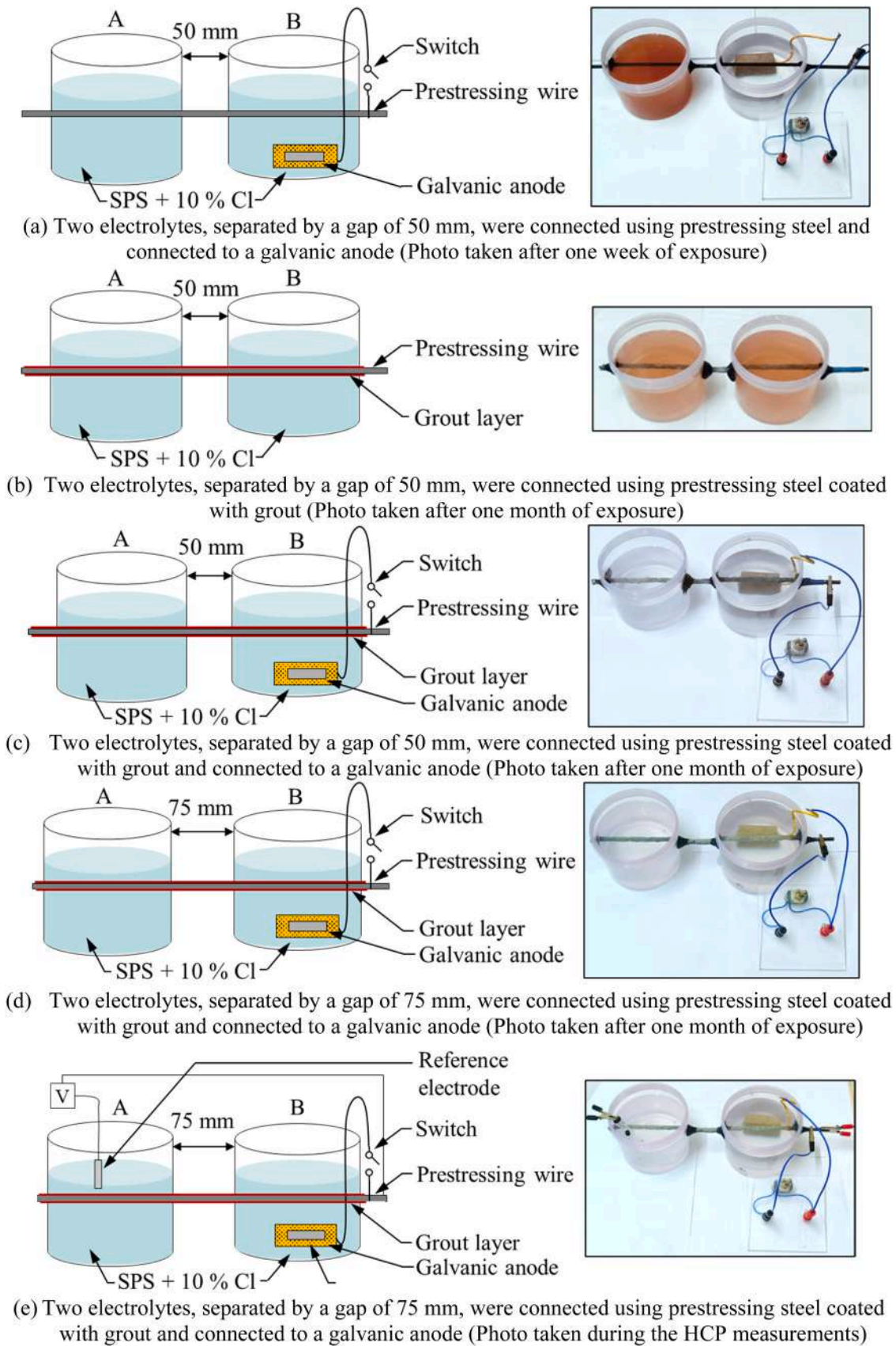
(a) Two electrolytes, separated by a gap of 50 mm, were connected using prestressing steel and connected to a galvanic anode (Photo taken after one week of exposure)

(b) Two electrolytes, separated by a gap of 50 mm, were connected using prestressing steel coated with grout (Photo taken after one month of exposure)

(c) Two electrolytes, separated by a gap of 50 mm, were connected using prestressing steel coated with grout and connected to a galvanic anode (Photo taken after one month of exposure)

(d) Two electrolytes, separated by a gap of 75 mm, were connected using prestressing steel coated with grout and connected to a galvanic anode (Photo taken after one month of exposure)

(e) Two electrolytes, separated by a gap of 75 mm, were connected using prestressing steel coated with grout and connected to a galvanic anode (Photo taken during the HCP measurements)

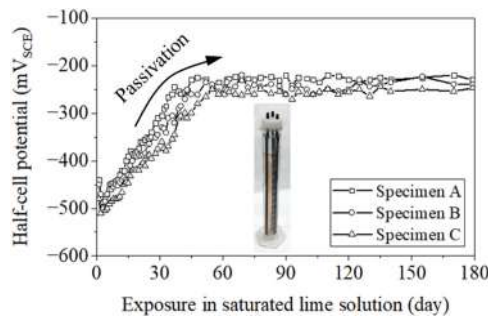**Fig. 11.** Experiments to validate the suitability of galvanic anodes in protecting the anchorage region.

Fig. 12. Evolution of the half-cell potential of prestressing steel specimens immersed in saturated lime solution.

Fig. 13. Variation in the half-cell potential before and after galvanic coupling.

the galvanic anode can protect the portion of strands and other metallic components outside the anchorage due to the availability of both ionic and electronic paths. To protect the portion of strands inside the anchorage, electron transfer from the galvanic anode can happen through the strands. However, the question is about the path for the transfer of ions inside the anchorage to complete the circuit. The anchorage plate is the element that separates the outside and inside of the anchorage. The anchorage plate has holes through which the strands pass through. In general, during the process of grouting, the grout filled through the grout port fills the duct, passes through the gap between the wires of the strand portions lying inside the holes of the anchorage plate, and then comes outside the anchorage plate. In this process, a layer of grout is formed over the strands. A series of experiments were conducted to prove that a layer of grout over the strand can provide a path for ionic conduction. The experiments were conducted in a setup consisting of two containers connected using prestressing steel with and without a layer of grout. In addition, experiments were conducted for two spacing of 50 mm and 70 mm. The experiments involving prestressing steel without a layer of grout represent an anchorage region with voids, whereas, the experiments involving prestressing steel coated with a layer of grout represent a re-grouted anchorage region. The details of the experiments are presented below.

A 5.2 mm diameter prestressing wire was taken and was positioned connecting two containers (A and B) with a gap of 50 mm in-between, as shown in Fig. 11(a). This arrangement replicates an anchorage region, with the containers replicating the inside and outside regions of the anchorage. The gap represents the width of the anchorage plate where strands pass through the strand holes. The typical width of an anchorage plate is 50 mm, and hence this spacing was chosen. A galvanic anode was placed in Container B and was connected to the prestressing wire at one end through the tie-wire. Both containers were filled with simulated concrete pore solution +10 % Sodium Chloride solution, completely submerging the prestressing steel. Such high concentrations of chlorides were selected to accelerate the corrosion process. The setup was kept aside without any disturbance for a week and was observed regularly. After about a week, it was observed that the portion of the steel in Container B with a galvanic anode remained uncorroded. However, the portion of the same prestressing steel in Container A started corroding, and the colour of the solution started changing to brown due to the mixing of rust with the solution. It was visually evident that the galvanic anode protected the prestressing steel from corrosion in Container B, whereas the galvanic anode was not able to protect the same prestressing steel in Container A. The reason for the corrosion of the steel is the unavailability of an ionic path for the galvanic anode to protect the portion of steel in Container A.

Similar experiments were conducted with prestressing wires coated with a thin layer of grout (PCG). Before the experiment, prestressing wires were coated with a layer of grout and immersed in a saturated lime solution to achieve passivation. The inset of Fig. 12 shows the photo of the three specimens A, B, and C immersed in a saturated lime solution. Fig. 12 shows the evolution of the half-cell potential (HCP) of the
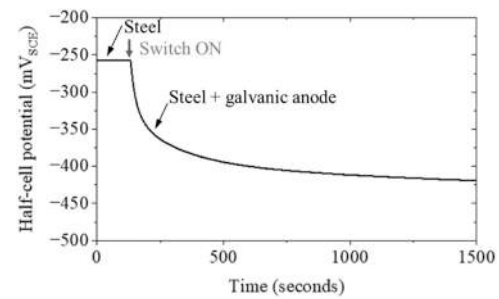
specimens after immersion in the saturated lime solution. The HCP of the specimens started shifting toward the electropositive direction and attained a steady state after 60 days. However, the exposure was continued for 180 days to achieve complete passivation of the steel. It can be inferred that a stable passive film has been formed on the specimens. Then, the specimens were removed from the saturated lime solution and three different experiments were conducted, which are described below.

In the first experiment, the prestressing steel was not connected to the galvanic anode and was exposed to the chloride solution, as shown in Fig. 11(b). The specimen started corroding after about a month. It can be inferred that the passive layer formed over the steel surface was not able to prevent the corrosion of steel after about a month. In the second and third experiments, the prestressing steels were connected to a galvanic anode as shown in Fig. 11(c) and (d). The spacing between the containers was increased to 75 mm, as shown in Fig. 11(d), to see the effect of increased spacing on the ionic conductivity. After about a month, no rust stains were seen on the solutions. No corrosion was evident on the portion of the steel in both containers in both cases. It can be inferred that the thin layer of grout around the steel would be sufficient to achieve the ionic path for a galvanic anode. However, to prove this mechanism electrochemically, HCP readings were taken on the steel specimens before and after connecting to the galvanic anode. The experimental arrangement is shown in Fig. 11(e). The switch was initially kept in the OFF position. The HCP of steel in Containers A and B, measured separately, were -250 mV$_{SCE}$ and -245 mV$_{SCE}$, respectively. The measurements were taken by keeping a saturated calomel reference electrode in the respective containers. Then, a potentiostat was connected to one end of the prestressing steel and the reference electrode was kept in Container A. The HCP measurement was started and the potential was measured ≈ -250 mV$_{SCE}$. Then, within a few seconds, as the experiment was running, the switch was turned ON. Fig. 13 shows the HCP response. It can be observed that the potential started jumping towards the electronegative direction when the switch was turned ON. It can be inferred that as soon as the switch was turned ON, the potentiostat started recording the mixed potential of steel and galvanic anode, due to the ionic conduction offered by the layer of grout. This proves that the layer of grout around the strand would help provide ionic conduction.

5. Procedure for chemical and electrochemical repair of anchorages

Fig. 14 shows schematics illustrating the step-by-step procedure for the chemical and electrochemical repair of post-tensioned anchorage. The steps are as follows:

1) Identify the grout port of the anchorage and clean it for any unwanted debris or loose grout particles, as shown in Fig. 14(a).
2) Inject 1 M Ca(OH)$_2$ solution into the anchorage through the grout port, as shown in Fig. 14(b). Continue injecting the alkaline solution till it fills the entire void region and comes out through the grout
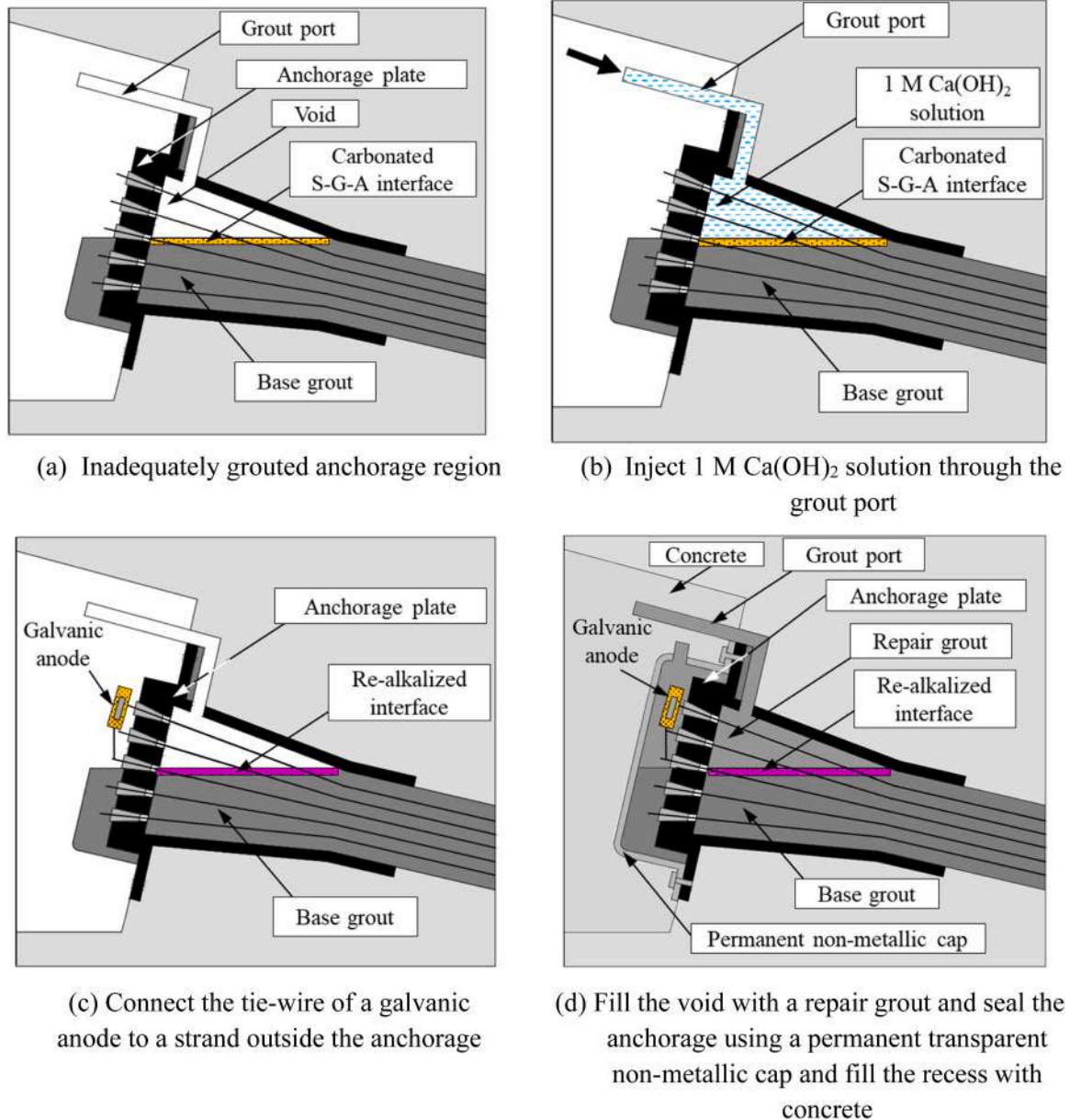
Fig. 14. Schematics illustrating the procedure involved in the chemical and electrochemical repair of post-tensioned anchorage.

port. After a week, remove the excess solution (if any) using a small vacuum pump.

3) Connect the tie-wire of a galvanic anode to a strand end outside of the anchorage, as shown in Fig. 14(c). The number of anodes can be decided based on the steel density ratio of the anchorage elements and according to the galvanic anode manufacturer's datasheet.

4) Inject pre-packaged cementitious repair grout (with a bleedwater volume of 0 %) through the grout port and fill the inside and outside regions of the anchorage, as shown in Fig. 14(d). Close the anchorage using a permanent transparent non-metallic cap and fill the recess region with concrete.

6. Recommendations for the protection of newly constructed anchorages

Anchorages are the critical elements of a PT concrete system, and multi-level corrosion protection systems should be used to protect them from corrosion. Fig. 15 shows the proposed multi-level protection systems for newly constructed anchorages, which are detailed below. Pre-packaged thixotropic grouts with high bleed resistance (zero bleed-water volume) shall be used to grout the tendons. This will prevent the formation of bleedwater and voids at the anchorage region. The grout port should be sufficiently large (diameter $\geq$ 30 mm) to allow a faster and easier flow of grouts into the ducts. Also, the grout port should be placed at the topmost region of the anchorage with sufficient clearance from the top to achieve complete filling of the ducts. Then, the anchorage should be sealed with permanent non-metallic transparent acrylic caps. The use of non-metallic acrylic caps will prevent galvanic corrosion between the various metallic components in the anchorage and also enable the visual assessment of the grouted anchorage. The anchorage cap should have a minimum cover of 50 mm from the outside face of the anchorage. Stainless steel bolts should be used to attach the cap to the anchorage plate. The stainless-steel bolt will have high corrosion resistance and will not corrode easily. The entire anchorage recess should be filled with fibre-reinforced concrete to prevent the formation of any shrinkage cracks. Then, a layer of waterproofing coating should be applied on the exposed concrete surface to completely seal the anchorage from humidity.
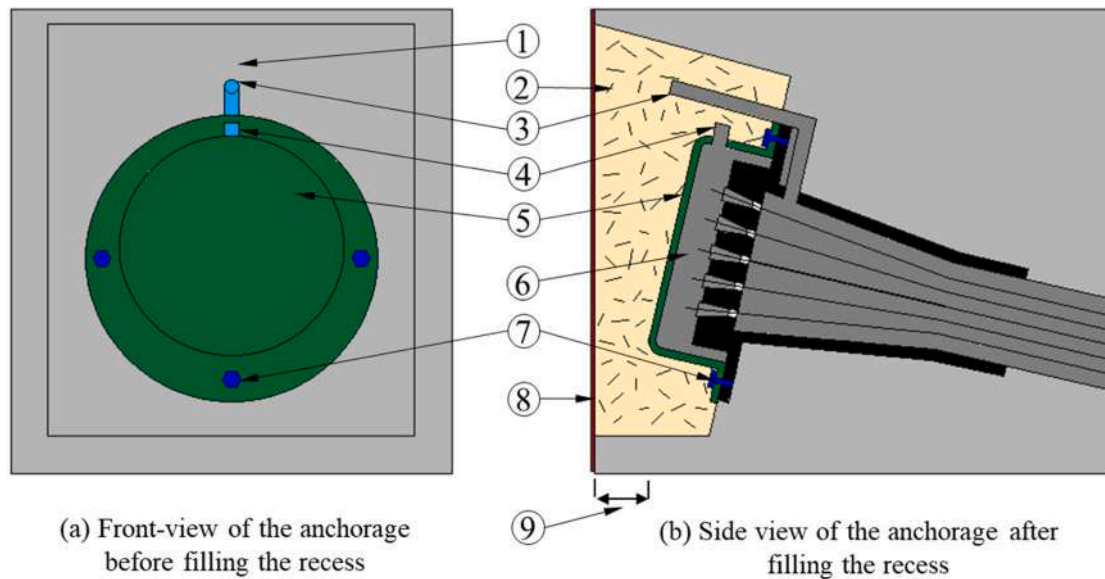
Note:
1 – Clearance for tendon grout port; 2 – Fibre-reinforced cover concrete;
3 – Tendon grout port (diameter ≥ 30 mm); 4 – Air vent; 5 – Transparent acrylic cap;
6 – Grout filling; 7 – Stainless steel screw; 8 – Waterproofing layer; 9 – Cover for acrylic cap ≥ 50 mm

Fig. 15. Proposed multi-level corrosion protection for newly constructed anchorage.

7. Conclusions and recommendations

In this study, the feasibility of chemical (re-alkalization) and electrochemical (galvanic cathodic protection) methods to repair the anchorage regions of inadequately grouted post-tensioned (PT) concrete systems was assessed. The following are the major conclusions drawn from the observations made in this research.

- Based on the carbonation studies, it can be concluded that plain cement grout (PCG) and site-batched grout (SBG) exposed to a Natural – Sheltered environment could carbonate to a depth of 5 to 6 mm, and after that, the increase in depth would be very minimal.
- The immersion studies showed that 1 M $Ca(OH)_2$ and 1 M Na_2CO_3 solutions can restore the pH of the carbonated grouts (PCG and SGB) within a day. Based on the results, it can be concluded that 1 M $Ca(OH)_2$ solution can be more effective than 1 M Na_2CO_3 solution in realkalizing the carbonated grouts, due to its high pH.
- The electrochemical impedance spectroscopy (EIS) studies on precorroded prestressing steel specimens indicated that the alkaline solutions (1 M $Ca(OH)_2$ and 1 M Na_2CO_3) were able to re-passivate the steel within one week of immersion. Based on the results, it can be concluded that 1 M $Ca(OH)_2$ solution can be more effective than 1 M Na_2CO_3 solution in re-passivating the embedded strands, due to its high pH.
- Based on the results, this study recommends the use of 1 M $Ca(OH)_2$ solution for seven days to re-alkalize the carbonated grout layer and re-passivate the exposed strands of the anchorage region. After realkalization, it is recommended to re-grout the voids with pre-packaged thixotrophic cementitious repair grout (with a bleed-water volume of 0 %).
- Based on the results from the experiments simulating the galvanic cathodic protection of the anchorages, it can be concluded that a thin layer of grout around the strand would be sufficient for a galvanic anode (connected to the strand-end outside the tendon anchorage) to protect the strand portions inside the anchorage region.
- Considering the practical challenges associated with implementation, this paper recommends the use of both chemical and electrochemical repair methods (redundant methods) to ensure complete protection of PT concrete systems to achieve the intended corrosion-free service life.

CRediT authorship contribution statement

Karthikeyan Manickam: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Radhakrishna G. Pillai:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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