

## Experimental Assessment of Cathodic Over Protection on Prestressed Wires under Variable Tensions

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### Abstract:

Cathodic Over-Protection is a critical issue that can affect the integrity and performance of prestressed wires embedded in concrete or mortar, widely used in numerous structural applications such as prestressed cylinder concrete pipes (PCCP). In this study, an experimental assessment was conducted to elucidate and evaluate the effect of Cathodic Over-Protection on most important mechanical properties and microstructures of prestressed wires under variable tensions. Over impressed cathodic protection currents were applied to six different samples of prestressed wires. Four samples were put under preset variable tensions ranging from 40% to 89% of their ultimate tensile stress (UTS), and a cathodic protection potential level of -1500 mv w/r (Ag/AgCl) half-cell, while the remaining two wire samples were put under only two preset tensions of 40% and 89% of their ultimate tensile stress (UTS), and a cathodic protection potential level of -1200 mv w/r (Ag/AgCl) half-cell. All six prestressed wire samples were immersed in a passivating alkaline environment similar to that found in mortar during the whole duration of the experiment.

Results have demonstrated that for the two applied levels of cathodic over-protection, corresponding significant changes in the mechanical properties and microstructural characteristics of these wires and these observed changes were more pronounced for those samples exposed to the -1500 mv potential level. Results also showed that for the two levels of protection potential, a reduction in UTS, and hardness as tension increases, while the % area reduction at the point of failure decreases. The negative effects of Cathodic Over-Protection on the mechanical properties of prestressed wires among other possible reasons may be due to the embrittlement of wires, which may be attributed to the observed bubbling of hydrogen gas on the wire surface during the experiment. Therefore, Hydrogen embrittlement phenomenon may be a possible cause of these changes requiring further experimental investigation.

**Keywords:** Prestressed steel wires, over cathodic protection and hydrogen embrittlement.

## الملخص

الحماية الكاثودية المفرطة هي مشكلة حرجة يمكن أن تؤثر على سلامة وأداء الأسلاك السابقة الاجهاد المدفونة في طبقة الملاط المكسوة به والتي تستخدم على نطاق واسع في العديد من التطبيقات البنائية مثل أنابيب الخرسانة الأسطوانية السابقة الاجهاد (PCCP). في هذه الدراسة المعملية، تم إجراء تقييم عملي لتوضيح وتقييم تأثير الحماية الكاثودية المفرطة على أهم الخواص الميكانيكية والبنية المجهرية للأسلاك السابقة الاجهاد تحت شحود متغيرة. تم تطبيق تيارات الحماية الكاثودية المفرطة على ست عينات مختلفة من الأسلاك السابقة الاجهاد. حيث تم وضع أربع منها تحت شحود متغيرة محددة مسبقاً تتراوح من 40% إلى 89% من إجهاد الشد الأقصى (UTS)، ومستوى جهد حماية كاثودية يبلغ -1500 ملي فولت نسبة الى نصف الخلية القياسية (Ag/AgCl)، بينما تم وضع العينتين الأخرين تحت شحود محددة مسبقاً بنسبة 40% و 89% من إجهاد الشد الأقصى (UTS)، ومستوى جهد حماية كاثودية يبلغ -1200 ملي فولت نسبة الى نصف الخلية القياسية (Ag/AgCl). جميع عينات الأسلاك الستة المجهددة تم غمرها في وسط قلوي يحاكي تلك الموجودة في طبقة الملاط طوال مدة التجربة. أظهرت النتائج المعملية انه بالنسبة للمستويين المطبقين من الحماية الكاثودية المفرطة تغييرات معتبرة في الخواص الميكانيكية والبنية المجهرية للأسلاك المشدودة وكانت أكثر وضوحاً في العينات المعرضة لمستوى جهد -1500 ملي فولت. كما أظهرت أيضاً أنه بالنسبة للمستويين من جهد الحماية، يحدث انخفاض في UTS والصلادة بشكل متناسب مع قيم الشد المطبق وتقل نسبة انخفاض المساحة عند نقطة الفشل. كما أظهرت الصور للبنية المجهرية للعينات الستة أيضاً تغييرات كبيرة عند مقارنتها بالعيينة المرجعية الغير معرضة للحماية المهبطية المفرطة. قد تكون التأثيرات السلبية للحماية الكاثودية المفرطة على الخواص الميكانيكية للأسلاك السابقة الاجهاد من بين الأسباب المحتملة الأخرى التي قد تسبب هشاشة الأسلاك، والتي قد تُعزى إلى تصاعد فقاعات غاز الهيدروجين على السطح أثناء التجربة. ويعتقد ان تكون ظاهرة هشاشة الهيدروجين سبباً محتملاً لهذه التغييرات التي تتطلب مزيداً من التحقيق المعلمي.

**الكلمات المفتاحية:** الأسلاك السابقة الاجهاد، الحماية الكاثودية المفرطة، الهشاشة الهيدروجينية

## INTRODUCTION:

In most environments, regardless of whether reinforcing steel or pre-stressing steel is used, concrete provides a relatively high degree of protection against corrosion and, in turn, the steel provides reinforcement for the concrete. The concrete produces a protective passivating film on

the surface of the steel, which is created by the high alkalinity (pH) of the concrete. Typically, the pH of the concrete is approximately 13. (Lambert, 2015). Concrete reinforced with steel is a durable construction product and should provide many years of maintenance-free use if properly designed and constructed. However, there are a significant number of cases where problems have occurred due to the corrosion of the steel reinforcement in the structures due to poor design and workmanship and as a result of exposure to aggressive environments, for example, the use of deicing salts on motorway bridges and marine structures due to their vicinity in chloride contaminated water. Pre-stressed steel can also corrode in a similar way as conventional reinforcing steel, but its impact could be greater, as stresses are higher and tendon diameters are smaller. Cathodic protection (CP) has been successfully used to mitigate corrosion by offering protection to buried and submerged metallic structures for almost two hundred years. (Broomfield, 2020). More recently, the method has been successfully applied to reinforced concrete. However, there is some concern about applying CP on pre-stressed tendons due to the risk of hydrogen embrittlement (HE), which may lead to premature rupture. It has long been recognized that over polarization by CP, for example, due to inadequate monitoring and control or the pick-up of stray currents from external sources such as DC traction or adjacent CP systems, can result in the generation of hydrogen, which, in turn, could lead to problems with embrittlement in high-strength tendons (Pedferri, 2020). However, research has been carried out over the years to assess its practical potential for use in pre-stressed concrete and the actual risk of susceptibility to stress corrosion cracking.

Due to the compression of concrete in pre-stressed concrete structures, cracking is better controlled and a reduction of the cross-sectional area of a member is enabled, thus offering an extended range of options for many types of structures including bridges and buildings. Pre stressed concrete tanks are used in water treatment and distribution systems, wastewater collection and treatment systems and stormwater management. Other applications include liquefied natural gas containment structures and bunds, large industrial process tanks and bulk storage tanks. A particular type of structure which will benefit from the research are bund walls constructed using the pre-load method. These provide secondary containment in the event of a rupture of holding tanks. Their construction involves winding highly tensioned tendons around the walls to provide support to the structure. Construction of these structures was widespread in the 1960s and asset managers are now facing growing concerns with regard to their safety.

Corrosion of the wire tendons has become an issue, and an assessment of their residual strength has been studied elsewhere. (O'Flaherty F. L., 2019).

CP of steel in concrete is a well-established and proven technique. It mitigates the steel corrosion process, eliminating the danger of further cracking and spalling and enabling the structure to reach its full design life. It has been successfully employed on both new (cathodic prevention) and existing (CP) reinforced concrete currently suffering from or at future risk of steel corrosion. It is well known in the infrastructure management industry that the risk of generating sufficient hydrogen during the application of CP means there are concerns over its use in pre stressed concrete. (Sanchez, 2016). HE can lower the fracture resistance of high-strength steels, especially if over- polarized. (O'Flaherty I. R., 2020).

Concrete structures adopt active tendons that consist of pearlitic cold-drawn wires or strands in prestressed and posttensioned structures. From the durability point of view, corrosion failures may occur by pitting or local corrosion due to the arrival of chlorides or the carbonation of concrete cover, causing a decrease in the local cross-section of the steel. Stress corrosion cracking together with hydrogen embrittlement have been also mentioned in many of the failures reported. However, the mechanisms of these two types of attacks have not been completely described yet. It is believed that hydrogen embrittlement could be one of the main reasons for the cracking of steel structures under stress (Eliaz, 2002).

The world estimated production of pearlitic-drawn wire is more than 25 million tons per year (Elices, 2008). Pearlitic steels have a ferrite matrix with cementite lamellae. The ferritic phase is made of  $\alpha$ -iron (body centred cubic lattice, bcc). To control and prevent the cracking of steel it is necessary to understand the chemical and physical properties of hydrogen inside bcc-iron.

There are two types of prestressing steel wires commonly used in prestressed concrete members:

1. Unalloyed, patented, cold drawn, stress relieved wires (some manufacturers do not stress relieve) or strand made of high carbon unalloyed steel.
2. Cold stretched rods made of low alloy steels, these steel grades have pearlitic structure and contain carbon in the range 0.66-0.93%.

The pearlitic steels have a good performance record in service but are prone to brittle service failures, especially when exposed to aggressive environmental conditions. One common cause of the sudden rupture of prestressed steel wires is cracking due to Hydrogen Embrittlement Stress

Cracking (HESC). According to the Institute for Building Materials and Building Structures, HESC accounts for approximately 35% of all brittle failures. (Khare, 2017)

Based on the current trends of growing application of steels with higher strengths (UTS > 1800 MPa) in construction of concrete structures, it appears the incidence of damage caused by hydrogen produced due to corrosion reactions may become more frequent in the presence of higher working stresses.

## **Aims and Objective**

Aim of this study is to experimentally assess the impact of cathodic over-protection on a specific mechanical properties U.T.S, hardness, reduction of area and the microstructure of the prestressed wires used in GMRP, the prestressed wires samples will be subjected to different levels of tensions and placed in an alkaline environment to simulate the similar surrounding the wires in actual PCCP. It is intended to apply two levels of impressed current cathodic protection of -1500 mv, and -1200 mv vs. Ag/AgCl standard Half-Cell under alkaline aqueous environment similar to that in mortar.

The Objective of the proposed is to conduct experimental tests to assess the susceptibility of the prestressing steel wires embedded in PCCP to changes in mechanical properties and microstructures as a result of applying over a preset impressed current of over- cathodic protection. Two level of CP potentials (-1200, and -1500 mv) vs. Ag/AgCl standard Half-Cell under simulated mortar service conditions. The wires were prestressed variable tensions ranging from 40% to 80% of their specific manufacturer UTS, and then immersed in an alkaline electrolyte (pH, 12—13). After a specified period of exposure, samples are withdrawn and visually inspected and their mechanical properties are measured as a function of applied tension and over-cathodic potential level. In addition, microstructure analysis is performed on samples of wire before and after exposure.

## **Experimental work**

### **Apparatus**

1. Six working samples made of 6.35 mm in diameter of high strength steel wires.
2. Six specially fabricated tension holding frames.
3. Six glass vessels, each has dimensions of (60 cm X 30cm X 30cm).

4. Two reference electrodes of (Ag/Ag Cl).
5. Multi-meter for measuring potential, current and resistance.
6. pH-meter.
7. Thermometer.
8. Six Rectifiers.
9. Six Auxiliary Electrodes.

### **Experimental Set-up**

The Six working steel wire samples used in this work were prepared as follows:

1. The six samples have been divided into two levels: the first level (-1500 mv) and the second level (-1200 mv), there are four samples in the first level (-1500 mv) with intensities of 40%,60%,79% and 89% of U.T.S and in the second level (-1200 mv), there are two samples with intensities of 40% and 89% of U.T.S, then removed from the tensile machine by its designated tension holding frame as explained earlier.
2. The samples were tensioned with the specified intensities at the laboratory of the Libyan Compony for Technical Consultations. The applied tensions on all the samples were confirmed, and markers were placed on each sample to measure the distance between these points. This was done to ensure the consistency of these distances and to ensure that the tension does not decrease in each sample. A minimum duration of one month was allocated for the samples to ensure the absence of any errors in the tension values.
3. Prepare the medium for the samples to simulate the real environment of the prestressed wires used in the transportation pipelines of Man-Made River.
4. The samples are coated with a layer of sulfur cement to simulate the conditions of the wire inside PCCP.
5. To achieving standardized conditions in four containers for fist level (-1500 mv), specifically regarding pH and temperature approximately 20 liters of deionized water added to each vessel and a certain amount of sulfur cement(400g) was mixed with deionized water and left to dry and formed into cubes, after that crushed it to smaller chunks and evenly distributed in all vessels and

left undistributed for at least 15 days after this period the pH value in all vessels stabilized around 12-13.

6. A potential measuring post made of copper wire was connected to one end of each working sample and the entire connection zone was covered by coal tar epoxy resin, and electrically insulated by means of tight plastic sleeve, Samples were electrically isolated from holding frames by placing a rubber tube between the sample and the frames, isolate the clams and prevent them from coming into contact with the frames by using a piece of rubber that has been tested to withstand tension and pressure. The purpose of isolating the samples from holding frames is to ensure that only current passes through the samples and that the voltage reading is correct for the samples only. The process of isolating samples was verified for about 20 days, and the process proved successful.

7. The four samples with varying tensions of first level (-1500 mv) were simultaneously placed on the same day and the same time, pH and voltage measurements were conducted for each sample every day for formation of the electrochemical passive layer on the wire surface of each sample (room temperature), and electrostatic natural potential of each working wire sample against a (Ag/AgCl) reference electrode placed in the same vessel for approximately one month.

8. The samples were kept inside the containers for a duration two-months, daily measurements of both potential and pH were taken to ensure the stability of the pH values and potential of the samples.

9. Once the necessary conditions were ensured for all the samples, over cathodic protection was initiated simultaneously on the samples at the first level (- 1500 mv) on the same day. This process lasted for a continuous period of 8 months, starting in January. During this timeframe, daily measurements of the potential and pH were conducted.

10. The same procedure that was implemented at the first level ( -1500 mv) were also applied at the second level (-1200 mv), the procedure was indeed initiated in the month of April and continued for another 8 months. Due to the limited availability of samples, only two samples were used at the second level (- 1200 mv), and applied two tensions 40% and 89% of U.T.S.

11. After approximately 8 months, the samples from the first level ( -1500 mv) removed and cleaned by deionized water. Subsequently they were placed in evacuated containers filled with silica gel to ensure their preservation and protection from external influences. Similarly, after

approximately 8 months, the same procedure was applied to the samples from level 2 (-1200 mv). This meticulous approach aimed to maintain the integrity of the samples and safeguard them from external effects.

12. Upon completion of the designated timeframe for both the first and second levels, the experiment was concluded. The samples were carefully extracted from their holding frames and thoroughly cleaned using deionized water. Subsequently, they were removed from the holding frames and placed in evacuated container. Several tests will be conducted, including the measurement of mechanical properties such as ultimate tensile strength (U.T.S), hardness and reduction of area.

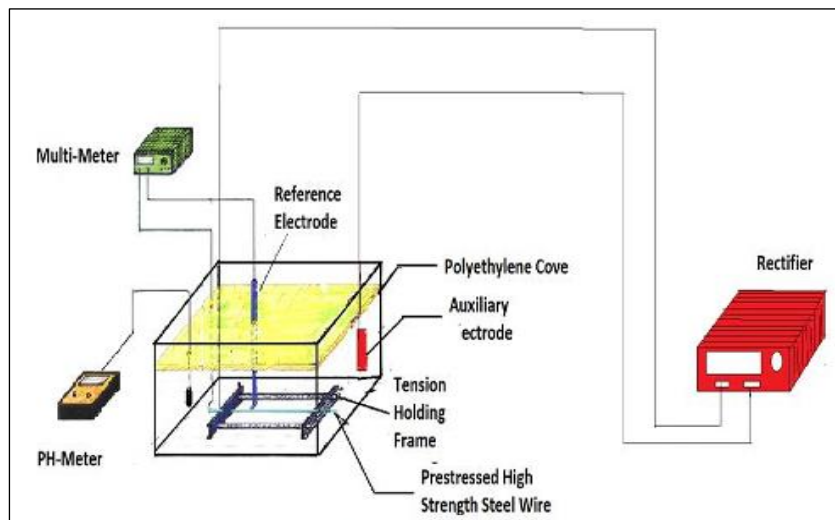


Figure1: Detailed Schematic View of Experimental Set-up of a Single Cell

## Results:

### Mechanical Properties of Reference Sample ( $S_0$ ):

Mechanical tests were first conducted on a reference sample cut from the same coil labeled  $S_0$  in to enable comparisons with similar tests performed on all samples subjected to two over cathodic protection levels; -1500 mv, and -1200 mv vs. (Ag/AgCl) half-cell under variable tensions during the duration of the experiment. The measured mechanical properties performed on the reference sample  $S_0$  are summarized in Table1

**Table1:** Summary of Measured Mechanical Properties of Reference Sample ( $S_0$ )

|  | $S_0$  |
|--|--------|
| <b>Ultimate Force (KN)</b>                   | 64     |
| <b>Hardness HB/30</b>                        | 323.3  |
| <b>Ultimate Stress (<math>N/mm^2</math>)</b> | 1777.9 |
| <b>Reduction of Area%</b>                    | 31.75  |

The following are summaries of all measured mechanical properties and microstructural analysis presented in tabular and graphical forms, which were performed on all tensioned wire samples after near eight months of exposure to the alkaline environment, subjected to two levels of over-cathodic protection potentials -1500 mv, and -1200 mv vs. to Ag/AgCl half-cell reference electrode.

#### **Mechanical Properties of (-1500 mV) Samples:**

**Table2:** Mechanical Properties for Samples at Level 1 (-1500 mv)

|  | $S_0$  | S1    | S2    | S3    | S4    |
|--|--------|-------|-------|-------|-------|
| <b>Ultimate Force (KN)</b>                   | 64     | 54.25 | 50.94 | 49.75 | 48.24 |
| <b>Hardness HB/30</b>                        | 323.3  | 291.2 | 278.7 | 259.7 | 248.7 |
| <b>Ultimate Stress (<math>N/mm^2</math>)</b> | 1777.9 | 1507  | 1415  | 1382  | 1340  |
| <b>Reduction of Area%</b>                    | 31.75  | 25.4  | 22.22 | 19.05 | 17.46 |

#### **Effect of Over Cathodic Protection on Mechanical Properties of Prestressed Specimens for Level 1 (-1500 mv):**

The chart clearly demonstrates the decline in the mechanical properties of the prestressing wires subjected to the first level of over cathodic protection, as compared to the reference sample **Figure2** and **Figure3** showed that.

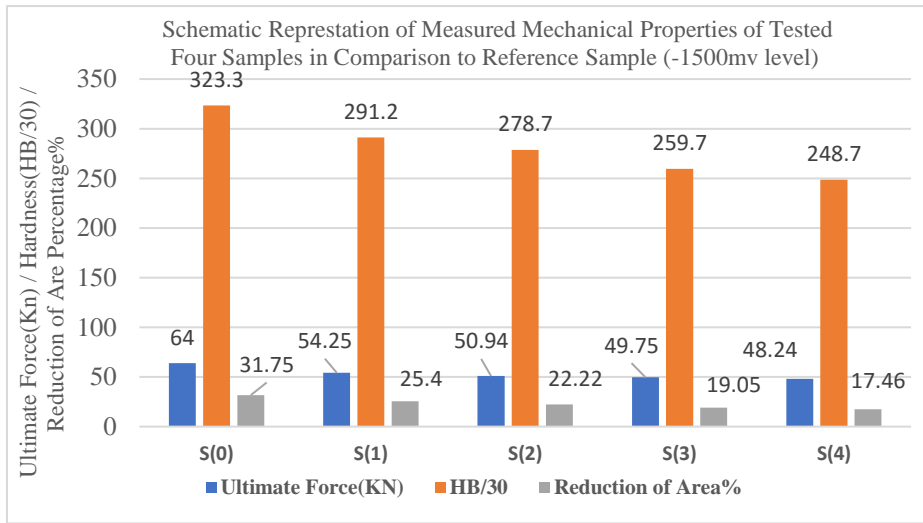


Figure 2: Schematic Illustration of Changes of Mechanical Properties of Samples Level 1 of Over-Cathodic Protection (-1500 mv)

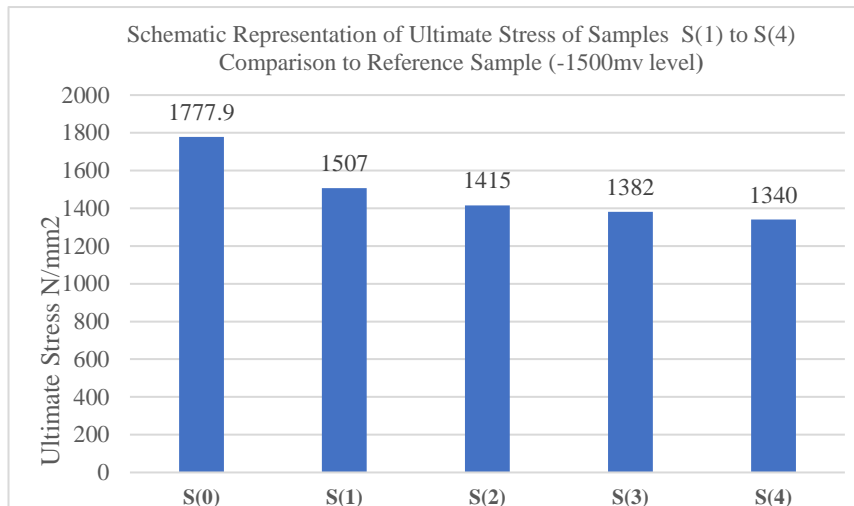


Figure 3: Schematic Illustration the Results of the Ultimate Stress for Samples at Level 1 (-1500 mv) Relative to Ag/AgCl

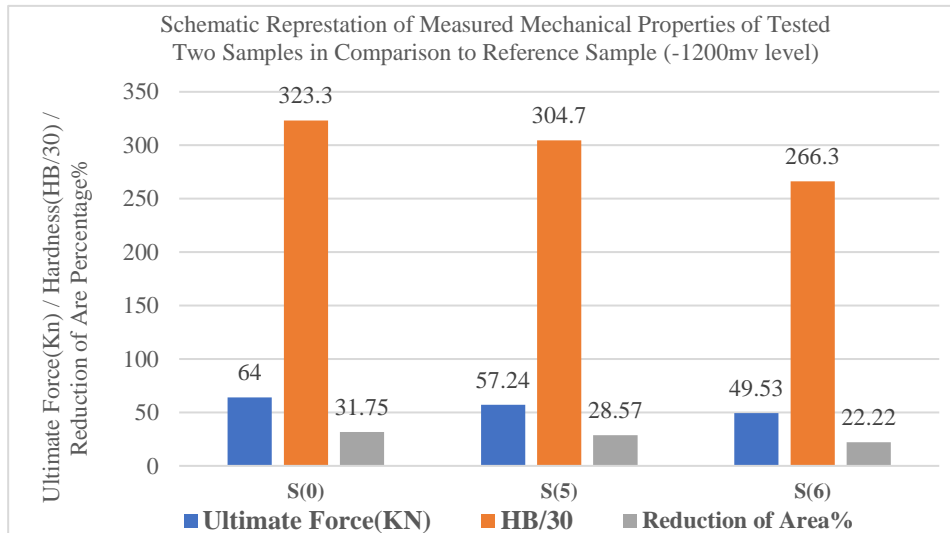
### Mechanical Properties of (-1200mV) Samples:

Table 3: Mechanical Properties for Samples at Level 2 (-1200 mv)

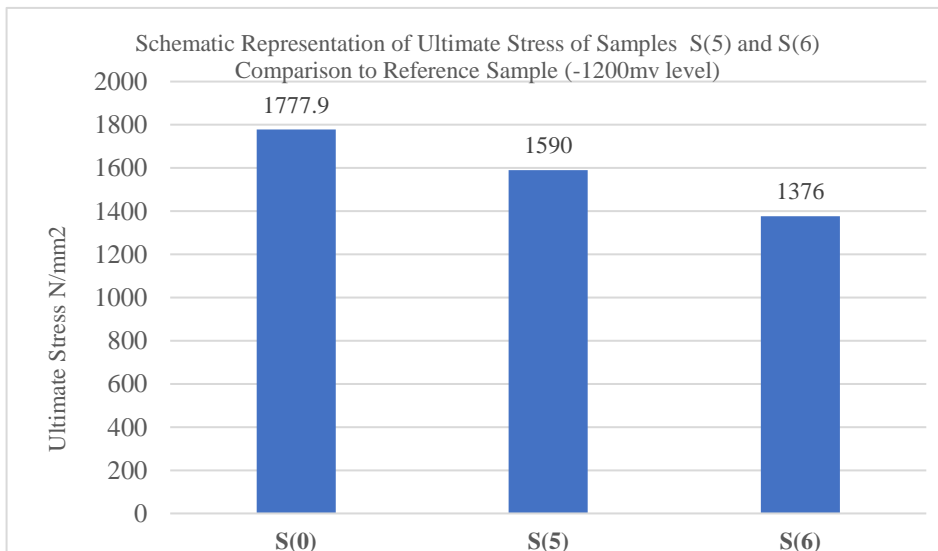
|                                      | S <sub>0</sub> | S <sub>5</sub> | S <sub>6</sub> |
|--------------------------------------|----------------|----------------|----------------|
| Ultimate Force (KN)                  | 64             | 57.24          | 49.53          |
| Hardness HB/30                       | 323.3          | 304.7          | 266.3          |
| Ultimate Stress (N/mm <sup>2</sup> ) | 1777.9         | 1590           | 1376           |
| Reduction of Area%                   | 31.75          | 28.57          | 22.22          |

**Effect of Over Cathodic Protection on Mechanical Properties of Prestressed Specimens for Level 2 (-1200 mv):**

The chart clearly demonstrates the decline in the mechanical properties of the prestressing wires subjected to the first level of over cathodic protection, as compared to the reference sample **Figure4** and **Figure5** showed that.



**Figure 4:** Schematic Illustration of Changes of Mechanical Properties of Samples Level 2 of Over-Cathodic Protection (-1200 mv)



**Figure5:** Schematic Illustration the Results of the Ultimate Stress for Samples at Level 2 (-1200 mv) Relative to Ag/AgCl

## Discussion:

The results obtained in this study were divided into two levels based on the degree of over cathodic protection applied to the six samples:

- Level 1 (-1500mv) relative to Ag/AgCl half-cell.
- Level 2 (-1200 mv) relative to Ag/AgCl half-cell.

The study examined the incurred influence of relatively high over-cathodic protection potential (-1500 mV vs. Ag/AgCl reference electrode) on mechanical properties of four different pre stressed wire samples, each with a different level of pre-stress of 40%, 60%, 79%, and 89% of UTS. Table 2 shows clear decline in mechanical properties of all 4 samples in comparison with those measured and summarized in Table 1 for the reference wire sample (unstressed and unprotected). It is evident that the observed effect is indirectly proportional to prestress level as follows:

### 1 Ultimate Tensile Strength and Ultimate Force:

All four wire samples experienced a significant reduction in ultimate tensile strength and ultimate force, ranging from 15% to 25% loss compared to the baseline. The higher the pre-stress level, the greater the reduction in tensile strength due to over cathodic protection.

- The graphical representations in Figure1 and Figure2 illustrate the decline of the mechanical properties of the pre-stressed wires due to the high over cathodic protection, this graph shows the reduction in ultimate tensile strength and ultimate force for the four wire samples with different pre-stress levels (40%, 60%, 79%, and 89% of the ultimate strength).

As the pre-stress level increases, the reduction in tensile strength becomes more pronounced, with the 89% pre-stressed sample experiencing the largest decrease compared to the reference (unprotected) sample.

### 2 Hardness HB/30

Hardness is a measure of a material's resistance to plastic deformation, typically indentation or penetration. It is an important mechanical property that is often used to evaluate the overall strength and durability of a material. Figure 1 and Figure 2 show changes in hardness after exposure to over-protection potential of tested wire samples with different pre-stress levels (40%, 60%, 79%, and 89% of the ultimate tensile strength). All four wire samples

experienced a significant reduction in hardness, ranging from 10% to 23% loss compared to the baseline reference wire sample (unprotected). The higher the pre-stress level, the greater the reduction in hardness due to over cathodic protection.

### 3 Reduction of Area

Reduction of Area may be considered as a measure of the ductility and toughness of a material. It is calculated as the reduction in the cross-sectional area of a specimen after it has been subjected to tensile testing, leading to failure. A higher reduction of area indicates greater ductility and the ability of the material to undergo plastic deformation before fracture. As the pre-stress level of the wires increased (from 40% to 89% of the ultimate tensile strength), the increase in the reduction of area becomes more pronounced. The 89% pre-stressed sample experienced the greater increase in reduction of area compared to the reference (unprotected) sample.

- Implications:

The reduction in reduction of area indicates a loss of ductility and toughness in the pre-stressed wires due to the over cathodic protection. This decrease in ductility suggests that the wires became more brittle and susceptible to premature failure under tensile or impact loading. The higher the pre-stress level, the more severe the loss of ductility, which could compromise the overall performance and reliability of the pre-stressed structures. It is evident in this work that high over-cathodic protection increased the reduction of area of the pre-stressed wires, with higher pre-stress level samples exhibiting a decrease in ductility and toughness. This decrease in ductility is of critical concern for long-term performance and integrity of pre-stressed structures exposed to such over cathodic protection.

Similar findings were obtained when only two wire samples prestressed to 40% and 89 % of UTS exposed to over-protection potential level of (-1200 mV vs. Ag/AgCl). Lesser Reduction in UTS, and HB/30 hardness with lesser increase in reduction of area when compared to the two corresponding samples at level of -1500 mv.

It may be concluded as a result of this work that the lesser the over-cathodic protection potential level, the lesser the negative impact on the mechanical properties of pre-stressed wires. This comparison highlights the importance of considering both the pre-stress level and the surplus in potential of cathodic protection above protection potential set by the adopted criterion. The choice of the appropriate cathodic protection potential is crucial to ensure the structural integrity.

## Conclusion:

This research has provided valuable insights into the detrimental effects of cathodic over-protection on the mechanical properties and microstructure of prestressed wires. The experimental findings on this study have revealed that prestressed wires subjected to high stress levels (40-89% of their ultimate tensile strength) and immersed in a passivating alkaline environment exhibit significant decline in their mechanical properties when exposed to cathodic potentials of -1200 mV and -1500 mV. This effect is more pronounced for the later level where more hydrogen bubbles are evolved on the surface. The phenomenon of hydrogen embrittlement may be responsible for these changes, as over-protection conditions facilitate hydrogen adsorption, leading to the formation of a weakening of the metal's mechanical properties. Finally, it may be concluded that experimental findings of this work underscore the importance of carefully managing cathodic protection levels to mitigate possible risks of developing hydrogen embrittlement on prestressing wires, particularly in high-stress applications such as in prestressed concrete cylinder pipes (PCCP).

## Recommendations:

- 1 The carbon content should not exceed 0.7% to ensure that iron carbide (cementite  $Fe_3C$ ) form with less amount, which can have undesirable effect on the mechanical properties of the steel.
- 2 More thorough scientific research is required to determine the optimum chemical compositions of prestressing steel wires that can be recommended to industries for manufacture and the selection of safe cathodic protection techniques.
- 3 Iron carbide, or cementite, can be effectively prevented and the corrosion resistance of the wire is enhanced by adding chromium to the composition.
- 4 Investigating how wire processing variables affect the quantitative development of compressive stresses on the wires and their interior microstructure during the cold drawing process is necessary.
- 5 It is required to carry out studies to determine how stress-relieving the wires affects corrosion and HESC behavior.
- 6 It is necessary to carry out experiments that examine how CP affects wires of various diameters at the same potentials (-1200 and -1500 mV relative to Ag/AgCl half-cell).

- 7 To protect the wires using a cathodic potential that does not reach the level that would cause hydrogen gas evolution. Specifically, it is recommended to use a criterion of a 100mv increase above the baseline, as this will ensure that hydrogen evolution is prevented.
- 8 Over cathodic protection can increase the susceptibility of prestressed wires to hydrogen embrittlement. Reducing the level of cathodic protection appears to lower the risk of hydrogen embrittlement in these wires.
- 9 Further experimental work is recommended to confirm precisely the presence and responsibility of hydrogen embrittlement for the observed decline of mechanical properties.

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