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# Experimental Assessment of The 100 mV Polarization Shift Criterion for Cathodic Protection Systems of the Prestressed Concrete Cylinder pipes

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ABSTRACT

In this work, an experimental study was carried out to evaluate the 100 mV polarization shift criterion for confirming the effectiveness of applied cathodic protection viz via zinc sacrificial anodes to arrest progress of corrosion in uncorroded or partially corroded high tensile grade prestressing steel wires of the same grade as the one used to manufacture the prestressed concrete cylinder pipes (PCCP).
Total number of 14 wire samples were placed under constant tension approximately 55% of their ultimate tensile strength by the use of specially designed and fabricated holding metal frames. All samples were individually immersed in glass vessels filled with alkaline solutions of pH around 12 and variable chloride ions concentration ranging from 500 to 3000 ppm. With the exception of one wire sample left unprotected; the remaining samples were cathodically protectedby systems of zinc sacrificial anodes such that an average measured polarization shift near 100 mV with variable chloride content in solution was maintained for 9 samples and near 75, 50, and 25 mV with constant chloride content of 3000 ppm.
Evaluation of mechanical properties of wire samples suggested that 100 mV criterionand more than sufficient to confirm the adequacy and effectiveness of zinc sacrificial anodes cathodic protection system to arrest progress of corrosion of partially corroded and uncorroded prestressing steel wires in alkaline passivating environment contaminated with chloride ions up to 3000 ppm in solution and for shifts in polarization as low as 25 mV.
It was also evident that corrosion progress in the prestressing steel wires can not be arrested in the 3000 ppm chloride environment without the application of cathodic protection.

***Keywords***: *Corrosion , Cathodic protection , 100 mV Polarization shift criterion , Prestressed concrete .*

## 1. Introduction

A large number of structures e.g. buildings , bridges ,dams, pressure vessels, strong tanks, piles, railway sleepers and nuclear reactor protective shells are made of prestressed concrete in which prestressing steel wires are put into a permanent state of tension to compensate for the inadequate tensile strength of the concrete. By prestressing the steel reinforcement, the concrete is placed under compression at normal working loads and hence it prevents tensile cracking in the concrete .Usually prestressing steel is 4-5 times stronger than mild steel.[1]

The optimum combination of high strength steel with high strength concrete makes prestressed concrete structural components lighter, stronger, and crack-free. Apart from the structural efficiency, it reduces the cost.

### 1.1. Construction of PCCP at Great Man-Made River Project

One of the single civil engineering projects of the 20th century is the great man made river project (GMRP) of Libya for water transportation for agriculture and industry. The cost of the transported under ground water from the aquifers in the Sahara desert to the coastal region will be substantially less than the desalination.

The project is aimed to convert thousands of hectares of semi-desert into rich fertile agricultural land leading Libya to become self sufficient in agriculture. The water will be available to manufacturing and processing industries. It will facilitate the expansion and growth of the industrial sector along the route of the pipeline.

The fresh potable water will be available to the inhabitants of many cities and villages along the pipeline route. The oil revenues have been made available to invest into the construction of GMRP to benefit all the community in this generation and for many generations to come. This project includes the state of the art construction facilities and a control system to operate the pipeline as per the experts estimation the fresh water supply will be available for a period over 50 years and hence the design life of the pipelines is to last this long.[2]

### 1.2. Manufacturing of Pre-stressed Concrete Cylinder Pipe (PCCP):

PCCP is designed to take optimum advantage of the compressive strength and corrosion-inhibiting property of Portland cement concrete and mortar and the tensile strength of prestressing wire. Each conveyance line PCC pipe is generally 4.0 m in internal diameter, 7.5 m in length, and weights over 70 tones. The pipe consists of an externally prestressed post tensioned concrete core 225 mm thick within which is embedded a thin steel cylinder as a watertight membrane. The prestressing is applied to the cured concrete core by over-wrapping with high tensile steel wire at a close pitch under uniform tension, anchoring the wire at each end of the pipe. Prior to the wire wrapping, bonding strips are welded between the anchor points to short out the wire turns and there by facilitate cathodic protection when needed. Steel joint rings welded to each end of the steel cylinder form a spigot and socket joint within the pipe wall thickness between adjacent pipes. Supplementary steel reinforcement strengthens the pipe ends.

Two rubber gaskets at the spigot and socket joints provide a watertight and flexible joint with some freedom of longitudinal and angular movement. High strength cement mortar spray applied on to the prestressing wire wrap provides mechanical and basic corrosion protection of the steel wire. Typical cross-section of the PCCP is shown in figure 1.

The PCCP is rigid, and relies on its inherent strength to resist internal pressure and external soil and surface loadings. Pipe design is in accordance with AWWA.

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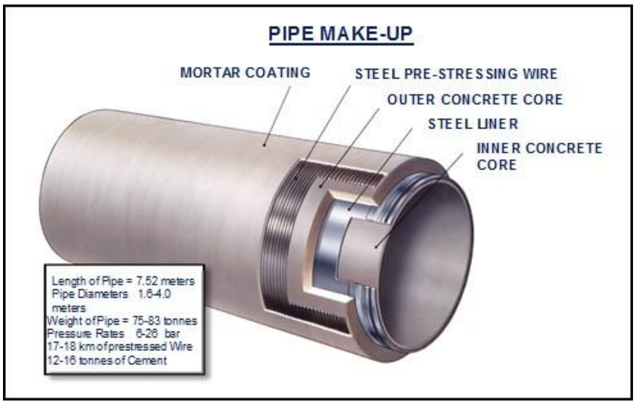


Figure 1 Typical Cross-Section of the PCCP

Standard C301. Pressure rating is based on the maximum steady state operating pressure plus a safety margin of 5 meters head of water, and accommodates transients up to 140% of rated pressure. Ratings for the primary conveyance system range from 6 bars to 28 bars in 2 bar increments, the different ratings being catered for in pipe manufacture by changes in prestressing wire diameter, pitch and number of layers.

During construction, all pipelines are made electrically continuous by the welding of continuity bars across each joint. All joints are cement grouted internally and externally. Special pipes and fittings are generally of fabricated steel construction, and are cement mortar lined to minimize galvanic differences, and thus provide corrosion protection.

Manholes are included on average every 615 meters to provide maintenance access and to carry the necessary air vacuum relief valves and blow-off lines, etc. At every manhole chamber, test leads are installed for use during corrosion survey and for future cathodic protection connection.

The PCCP prestressing wires are protected against corrosion and mechanical damage by a cement mortar coating. In non corrosive soil the pipe was installed un-coated only covered by cement mortar (this called WHITE pipe), while in aggressive ground conditions, black coal tar epoxy barrier coating was applied to the pipe surface to supplement the protection provided by the cement mortar coating (this is called BLACK pipe).

For the corrosion monitoring and the possibility of applying Cathodic Protection (CP) at any stage during the project service life, all pipe joints were provided with continuity bonds, and CP test leads were installed at all appurtenant structures.

The (CP) systems are designed to achieve pipe-to-soil potentials of -710 mV on potential with respect to a $Cu/CuSO_4$ reference electrode. Magnesium and zinc sacrificial anodes were initially used in Black pipes areas where soil resistivity is very low. They were selected over impressed systems, because of the susceptibility of the prestressing wire to hydrogen embrittlement so it is important to limit the protection levels to avoid hydrogen evolution on the wire surfaces.

The project experienced 4 catastrophic failures during the year 2000, (after 10-years of operation) in the non coated non-CP areas, and from the technical investigation of these four failures, a project policy decision was taken by GMRP-Authority to provide cathodic protection for the entire of the GMR project to cover about 3000 km of large diameter PCCP.[3]

All failures were located in the White pipe areas characterized by soil of high resistivity where it was virtually impossible to polarize the pipe to the potential of -710 mV by the use of zinc sacrificial anode CP systems. Thus it was decided by the project authority to adopt the 100 mV polarization shift criterion to confirm the adequacy and effectiveness of installed CP systems to prevent any further PCC pipes deterioration due to corrosion of the prestressing wires coated by mortar saturated with high concentration of chloride ions.

Hence the objective of this work is to experimentally evaluate the 100 mV polarization shift criterion for confirming performance and the degree of effectiveness of applied sacrificial anode CP systems of high tensile grade steel wires under tension exposed to corrosive environments of various chloride contents.

Therefore an experimental model was designed and developed to simulate zinc sacrificial anode cathodic protection systems of prestressing steel wires under tension immersed in an alkaline solution with various chloride contents. The 100 mV polarization shift criterion was implemented on all tested samples for the whole period of the experiment. Mechanical properties of tested wires were checked prior and after continuous exposure to prove or disprove the adequacy and effectiveness of the level of protection offered by the applied CP system.[4]

## 2. Experimental

The experimental setup employed in this work is shown and described in Figure 2, and since it was intended in this work to simulate as close as possible the real physical conditions surrounding the high strength steel wires in concrete pipes, thus it was prudent to place and maintain all relevant wire samples under tension equal to 70% of their U.T.S in PCCP. To achieve this objective 14 tension holding frames were especially designed, fabricated and then tested via strain gauge. Figures 3(a,b) give schematic description of one of these frames.

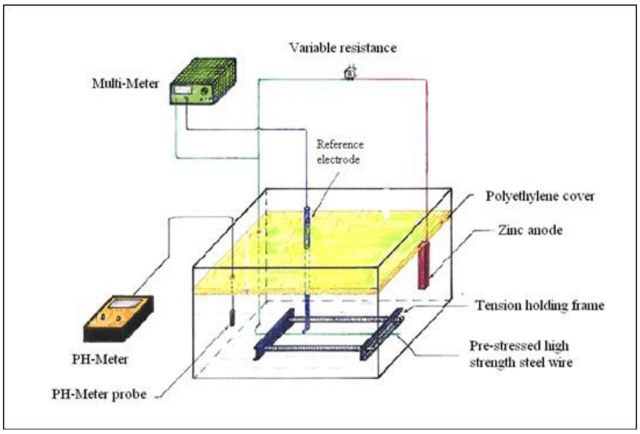


**Fig. 2:** Detailed schematic view of experimental set-up of a single cell

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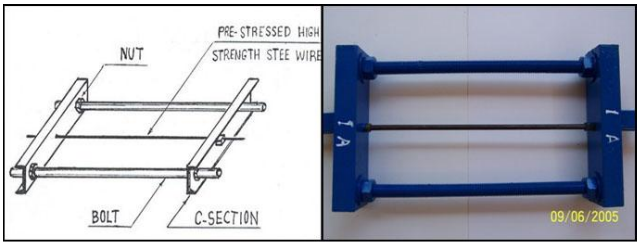


(a) (b)

**Fig. 3:** (a) A Schematic Diagram of An Assembled Tension Holding Frames. (b) A photo of An Assembled Tension Holding Frames.

The fourteen working high strength steel wires samples ( 6.35 mm in diameter ) were supplied from GMRA PCCP manufacturing plant in Brega. Thirteen of them were removed from corroded pipes, and one was cut from a new coil. The metallurgical composition and mechanical properties as certified by the wire manufactures is summarized as follows: Carbon steel (carbon 0.8-0.84%, 0.85-1.00%Mn, 0.030 %Max S, 0.035% Max P, 0.200.35% Si). Typical mechanical properties are presented in Table 1.

**Table 1.**Typical Mechanical Properties of Prestressing Wires

| Tensile Strength | U.T.S (MPa) | | Reduction in Area |
|---|---|---|---|
| Min(MPa) | Min | Max | Min (%) |
| 1655 | 1680 | 1860 | 30 |

Each wire sample was subjected to a tensile force of 30 KN and then held in one of the tension holding frames as described earlier before it was released from tensile machine. Periodic testing of each wire sample held in its frame was conducted via a strain gauge to insure that tension is maintained. All samples were coded with identifiable serial numbers S1 to S14 by the use of water proof marker as shown in figure (3b). Each vessel of the 14 used in this work was first washed thoroughly and detergent and then rinsed with portions of distilled water and then were filled with approximately 10 Liters of distilled water. Chunks of cement mortar of the same quality as specified for PCCP manufactured in Brega plant were placed in all vessels to produce a saturated alkaline solution of a pH above 12, simulating as much as possible the real condition of steel prestressing wires embedded in mortar coating of a PCCP. The fourteen working steel wire samples used in this work were prepared as follows:-

1. All samples were first cut in 500 mm segments uniform in shape and in length.
2. Each sample was subjected, by means of a tensile machine, to 30 kN tensile forces to produce a tension equivalent to 55% of U.T.S. Then it was removed from the tensile machine by its designated tension holding frame as explained earlier.
3. 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.
4. Each working wire sample is passed through the 10 mm diameter hole and held by two metal clamps equipped with a pvc plate on the inner side of each clamp to provide for electrical insulation of the sample from frame.
5. All samples were numerically coded in the same manner as the tension holding frames described earlier, i.e. S1 to S14.
6. Each tension holding frame with its fastened working wire sample was placed in its designated glass vessel filled with distilled water and concrete mortar chunks.
7. The formation of the electrochemical passive layer on the wire surface of each sample was confirmed through periodic measurements of pH, temperature, and electrostatic natural potential of each working wire sample against a (Ag/AgCl) reference electrode placed in the same vessel for approximately 3 days.
8. The amount of pure sodium chloride salt required to achieve the specified chloride concentration for in each vessel was first weighted, and then dissolved in each vessel. Table 2 gives a summary of the initial wire condition, chloride concentration, and required shift in potential of each sample after CP was applied in each vessel.
9. The electrostatic natural potential of each wire sample was established during the first week through daily measurements of pH, temperature and the potential of each sample until a stable and reproducible measurement of potential is attained i.e. the natural potential of this wire sample in this given prescribed conditions.

**Table 2**. Summary of Initial Wire Condition, Chloride Conc., and Potential Shift in All Vessels.

| Sample No | Wire condition | Vessel No | Chloride concentration ppm | CP criteria mV |
|---|---|---|---|---|
| S1 | corroded | V1 | 500 | 100 |
| S2 | corroded | V2 | 750 | 100 |
| S3 | corroded | V3 | 1000 | 100 |
| S4 | corroded | V4 | 1250 | 100 |
| S5 | corroded | V5 | 1500 | 100 |
| S6 | corroded | V6 | 2000 | 100 |
| S7 | corroded | V7 | 2500 | 100 |
| S8 | corroded | V8 | 3000 | 100 |
| S9 | corroded | V9 | 3000 | 710 |
| S10 | Not corroded | V10 | 3000 | 100 |
| S11 | corroded | V11 | 3000 | 75 |
| S12 | corroded | V12 | 3000 | 50 |
| S13 | corroded | V13 | 3000 | 25 |
| S14 | corroded | V14 | 3000 | 0 |

10. A zinc sacrificial anode was placed in each vessel and connected in an electrical circuit with a variable resistance to control the amount of current flowing in circuit of the applied cathodic protection such that the measured on potential of each working sample is constantly at a value shifted 100 mV from its pre-determined natural potential. It is worth mentioning here that some trials were carried out ahead of this step by

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introducing an interrogator precision switcher in circuit to experimentally confirm that IR drop in such conductive solution is negligible, and hence it was decided that only ON potential will be measured and used to establish the required shift in potential. Figure (2) gives schematic representation of the applied C.P circuit. Table 2 gives a summary of the observed condition of all samples along with measured shifts in potential.

11. A polystyrene cover was placed on the water surface in each vessel in order to minimize the evaporation rate and amount of atmospheric CO2 gas being dissolved into the water from air.
12. Measurements of pH, temperature, and potential were taken on daily basis with continuous monitoring of all samples to make any necessary adjustments in the variable resistance such that the required shifts in potential are maintained during the duration of the experiment.
13. Periodic Sampling and chemical analysis of water in each vessel was carried out to check for chloride concentration and if any noticeable reduction is observed, a make up amount of sodium chloride salt is added to the solution.
14. Any observed lowering in water level in each vessel due to natural evaporation was periodically corrected by addition of fresh amounts of distilled water.
15. After eight months of continuous daily monitoring of all samples, it was decided to stop and simultaneously withdraw all samples from all vessels. They were first dried, and then cut in 300 mm segments which represent the exposed part of the samples. And after they were visually observed and photographed they were all placed in container with silica-jell to prevent any effect of air humidity before mechanical tests are conducted. 15. Mechanical tests including tensile test and hardness test were performed at Central Research Laboratories in located in Tripoli to quantify any observed changes in mechanical properties incurred on tested samples due to exposure to solutions of variable chloride content and being at the same time under an applied cathodic protection in accordance to the adapted criterion.

## 3. Results and Discussion

Figures 4 and 5 give graphical representation of the variation of the measured potential of samples S8 (3000 ppm; 100 mV shift), and S13 (3000ppm; 25 mV shift) as a function of time in days, covering the whole period of this study.

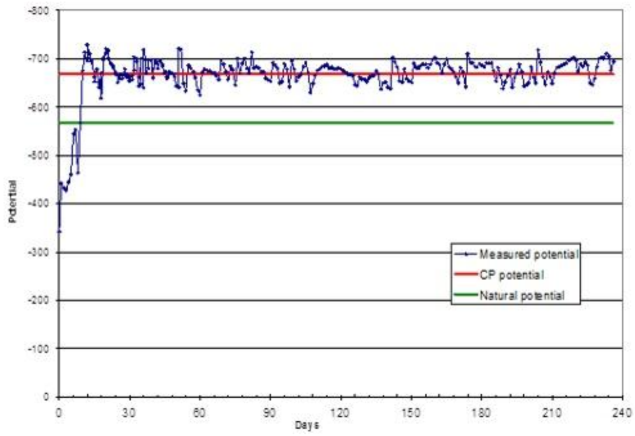


**Fig. 4:** Potential for Sample (S8).

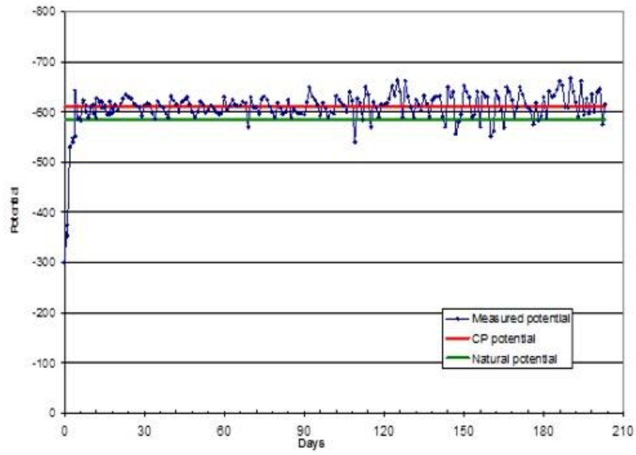


**Fig. 5:** Potential for Sample (S13)

Table 3 presents a summary of the measured average polarization shift in mV defined as the difference between the overall averages applied CP potential measured in all days, and the established natural potential for each sample. It is noted that the measured average values is slightly above the intended polarization shift of 100, 75, 50, and 25 mV respectively for all samples. This deviation was unavoidable since; polarization and depolarization are dynamic processes constantly changing with many variables controlling in the bulk solution away from the surface of each sample [3]. And thus it was virtually impossible to stabilize potential readings during time interval between two consecutive ones.

**Table 3**. Summary of Potential Polarization Shift of All Samples.

| Sample No. | Natural Potential (mV) | Average Applied CP Potential (mV) | criterion Polarization Shift (mV) | measured Average Polarization Shift (mV) |
|---|---|---|---|---|
| S1 | -558 | -667.0 | 100 | 109.0 |
| S2 | -585 | -695.2 | 100 | 110.2 |
| S3 | -552 | -657.5 | 100 | 105.5 |
| S4 | -580 | -687.4 | 100 | 107.4 |
| S5 | -540 | -646.7 | 100 | 106.7 |
| S6 | -557 | -664.8 | 100 | 107.8 |
| S7 | -572 | -679.5 | 100 | 107.5 |
| S8 | -568 | -675.1 | 100 | 107.1 |
| S10 | -570 | -676.9 | 100 | 106.9 |
| S11 | -540 | -623.0 | 75 | 83.0 |
| S12 | -541 | -604.5 | 50 | 63.5 |
| S13 | -585 | -613.4 | 25 | 28.4 |

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Figure 6 gives a graphical representation of the average polarization shift measured for all samples in comparison to the intended nominal values.

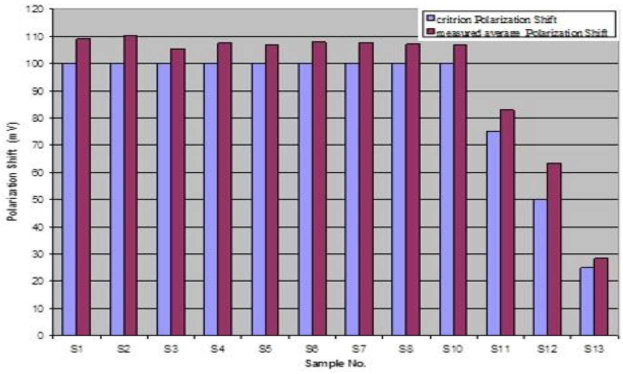


**Fig. 6:** Summary of Potential Polarization Shift of All Samples.

After each sample was subjected to a tensile test, a force-elongation curve was plotted automatically by computer. Figures 7 to10 show the force-elongation curves produced for all the samples. All samples show close to normal curves when compared to reference sample S15, indicating that applied cathodic protection was sufficient and effective in arresting the progress of corrosion in the presence of high chloride concentration in the solution. Sample S14 showed the smallest ultimate tensile strength and elongation before failure among all samples. This behavior was expected since no cathodic protection was applied. Thus corrosion process in this sample was progressing in spite of the existing passivating alkaline solution, resulting in the observed deterioration of its mechanical properties. This result confirms that electrochemical passivity will not be sufficient to arrest corrosion in highly chloride contaminated environments in absence of external cathodic protection.

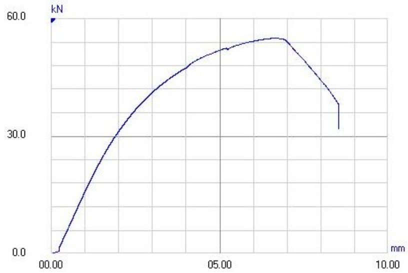


**Fig. 7:** Load-elongation Curve for S8.

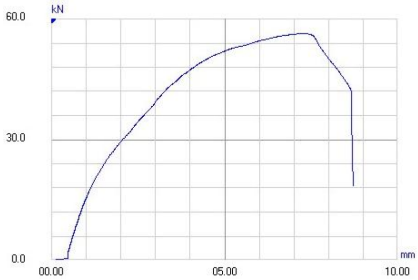


**Fig. 8:** Load-elongation Curve for S13.


**Fig. 9:** Load-elongation Curve for S14.


**Fig. 10:** Load-elongation Curve for S15.

Table 4 shows a summary of all measured mechanical properties for all samples, i.e., ultimate tensile strength (U.T.S), elongation, reduction in area, and hardness.

**Table 4.** Mechanical Properties of Wire Samples

| Sample No. | U. T. S. (MPa ) | Elongation ( % ) | Reduction in area (%) | Hardness HB-30 |
|---|---|---|---|---|
| S1 | 1781.8 | 1.439 | 48.66 | 389.3 |
| S2 | 1783.2 | 1.333 | 46.38 | 366.1 |
| S3 | 1802.4 | 1.370 | 46.38 | 376.1 |
| S4 | 1783.5 | 1.418 | 46.38 | 358.8 |
| S5 | 1795.2 | 1.447 | 47.52 | 366.1 |
| S6 | 1735.4 | 1.461 | 48.66 | 383.2 |
| S7 | 1779.3 | 1.307 | 46.38 | 379.9 |
| S8 | 1791.7 | 1.303 | 46.38 | 379.9 |
| S9 | 1743.9 | 1.418 | 45.22 | 362.4 |
| S10 | 1778.7 | 1.408 | 44.05 | 377.1 |
| S11 | 1785.3 | 1.375 | 44.05 | 365.8 |
| S12 | 1735.5 | 1.384 | 47.52 | 353.0 |
| S13 | 1786.2 | 1.498 | 47.52 | 386.5 |
| S14 | 1341.6 | 0.680 | 35.50 | 375.1 |
| S15 | 1773 | 1.370 | 46.38 | 364.9 |

Figures 11 to 14 give graphical comparisons between measured mechanical properties of all samples. It can be clearly noted that no significant differences in measured hardness of the catholically protected samples when compared to those measured for the non protected ones. It is also evident from these graphs that sample (S14), the non protected one gave lower ultimate tensile strength, % elongation, and % reduction area due to the lack of cathodic protection in high chloride concentration environment as mentioned earlier.

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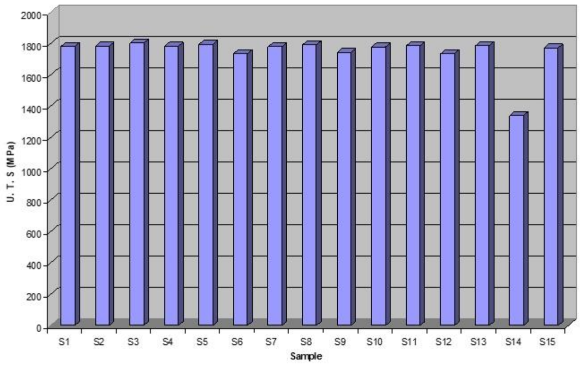


**Fig. 11:** Effect of Cathodic Protection on Ultimate Tensile Strength.

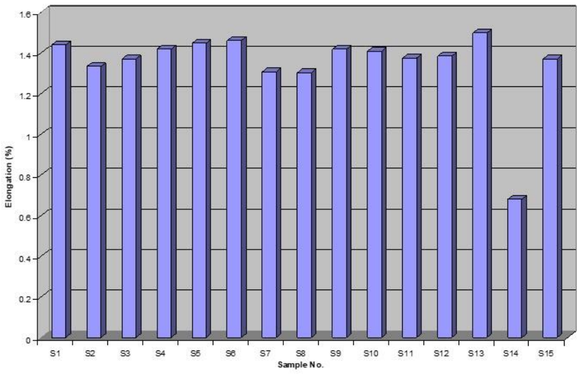


**Fig. 12:** Effect of Cathodic Protection on Elongation

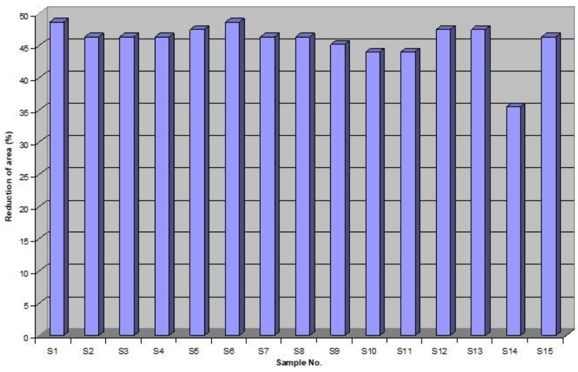


**Fig. 13:** Effect of Cathodic Protection on Reduction of Area

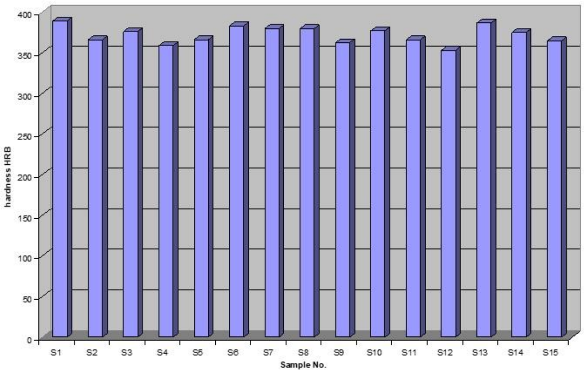


**Fig. 14:** Effect of Cathodic Protection on Hardness

Figures 15 a, b, and c show the SEM micrographs of the fracture surface of sample S8. The ductile feature and necking are clearly visible in those micrographs. These features indicate that applied cathodic protection was incapable of producing enough hydrogen to cause hydrogen embitterment which usually leads to failure mode similar to that observed in stress corrosion cracking.

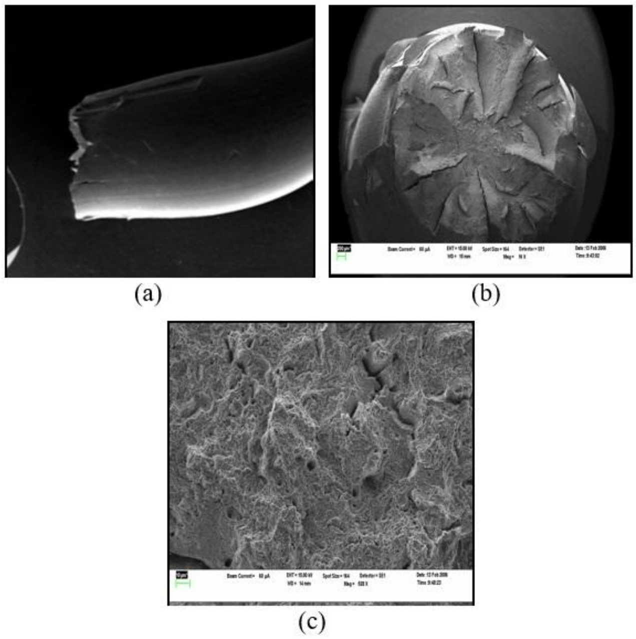


**Fig. 15:** SEM Micrograph for Sample (S8).

Figures 16(a), (b), (c), and (d), figure 17 show similar results for samples S13, and S14 respectively confirming the same conclusion stated for sample S8.

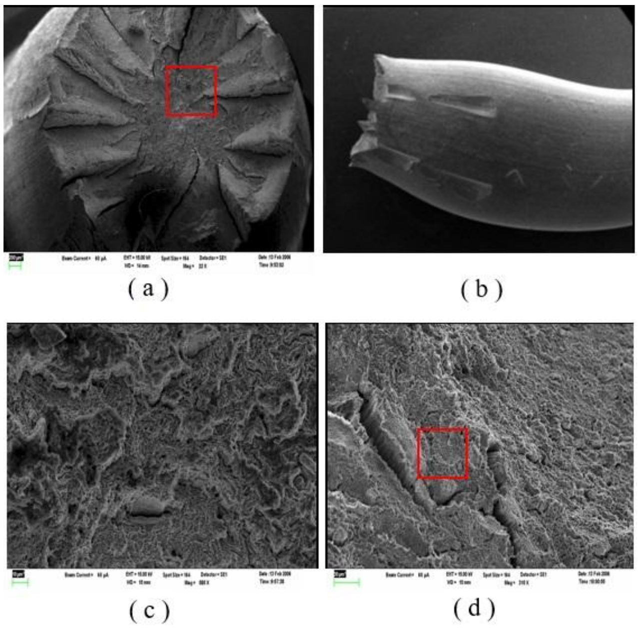


**Fig. 16:** SEM Micrograph for Sample (S13).

Table 5 summarizes the results of performance for the applied cathodic protection subjected to different protection criteria. It was found that the application of cathodic protection to partially corroded samples stops the corrosion in all cases studied in this work even in presence of as high chloride concentrations as 3000 ppm. While in the case of sample S14 (non- protected) a severe corrosion is observed resulting in poor mechanical properties

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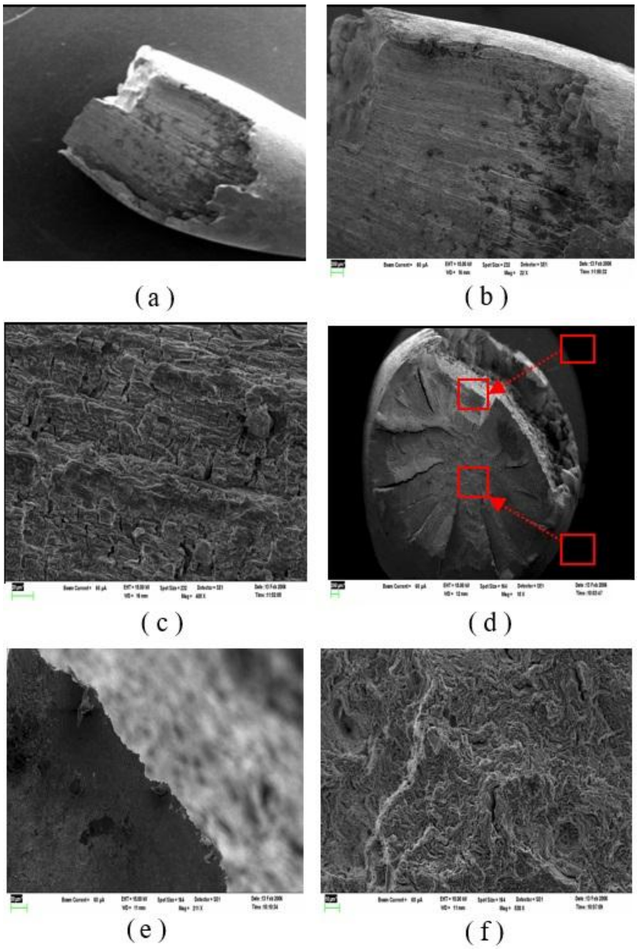


**Fig. 17:** SEM Micrograph for Sample (S14).

**Table 5.** Summary of CP results.

| Sample No | Chloride concentration ppm | CP levels mv | Status of applied cathodic protection |
|---|---|---|---|
| S1 | 500 | 100 | Sufficient and effective |
| S2 | 750 | 100 | Sufficient and effective |
| S3 | 1000 | 100 | Sufficient and effective |
| S4 | 1250 | 100 | Sufficient and effective |
| S5 | 1500 | 100 | Sufficient and effective |
| S6 | 2000 | 100 | Sufficient and effective |
| S7 | 2500 | 100 | Sufficient and effective |
| S8 | 3000 | 100 | Sufficient and effective |
| S9 | 3000 | (-710) on potential | Sufficient and effective |
| S10 | 3000 | 100 | Sufficient and effective |
| S11 | 3000 | 75 | Sufficient and effective |
| S12 | 3000 | 50 | Sufficient and effective |
| S13 | 3000 | 25 | Sufficient and effective |
| S14 | 3000 | 0 | Insufficient and ineffective |

## 4. Conclusion

In this work, the 100 mV polarization shift criterion for the assessment of effectiveness of zinc-sacrificial anodes cathodic protection systems to arrest corrosion in new and partially corroded prestressing steel wires was experimentally evaluated and tested in chloride contaminated aqueous alkaline medium similar to that surrounding environment of prestressing steel wires in PCCP,.

Nine partially corroded and one uncorroded randomly selected samples of steel prestressing wires were immersed in highly rich alkaline aqueous solutions maintained at a pH around of 12 with chloride concentration ranging from 500 up to 3000 ppm. All samples were cathodically protected by a system of sacrificial zinc anodes such that their on-potentials were shifted 100 mV from their natural potentials. Three extra samples were immersed in 3000 ppm chloride solutions and protected under 75, 50, and 25 mV potential shifts in an attempt to establish, a lower limit of the extent of applicability of this criterion under the worst chloride concentration in the surrounding medium.

Experimental results showed that the 100 mV polarization is a valid and more than sufficient criterion to assess the effectiveness of the applied zinc-sacrificial anodes cathodic protection system to arrest corrosion progress in partially corroded and uncorroded prestressing steel wires in alkaline passivating environment contaminated with chloride concentration up to 3000 ppm. The same conclusion was also established even for shifts in polarization as low as 25 mV. This is in full agreement with previous findings by Silvia et. Al. [5].

It was also evident that corrosion of the prestressing wires can not be arrested in 3000 ppm chloride contaminated medium in the absence of cathodic protection. Electrochemical passivity generated on the surface of the wires by immersion in alkaline solution was not sufficient to provide protection against the progress of corrosion.

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