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O'FLAHERTY, Fin <http://orcid.org/0000-0003-3121-0492>, ELOMARI, Ibrahim R. <http://orcid.org/0000-0002-3841-9486> and LAMBERT, Paul <http://orcid.org/0000-0002-2815-1674>

Influence of accidental over-polarisation on the mechanical properties of cathodically protected pre-tensioned tendons

Fin O'Flaherty[1], Ibrahim R. Elomari[2], Paul Lambert[3]

Centre for Infrastructure Management, Materials & Engineering Research Institute, Sheffield Hallam University, Howard Street, Sheffield, S1 1WB, UK

[1] Correspondence: Fin O’Flaherty, Sheffield Hallam University, S1 1WB, Sheffield, UK, f.j.oflaherty@shu.ac.uk;

Orcid IDS: [1]0000-0003-3121-0492; [2]0000-0002-3841-9486; [3]0000-0002-2815-1674

Abstract

This paper investigates the performance of pre-tensioned tendons deliberately exposed to higher than normal impressed current cathodic protection (ICCP) to replicate accidental over-polarisation. Plain ungalvanised tendons, 5.4mm Ø, were pre-stressed in moulds and cast in mortar. Two levels of pretensioning were investigated, low (~30% ultimate tensile strength [UTS]) and high level (~80% UTS). Three different degrees of corrosion with target losses of cross-sectional area of 0%–1%, 2%–4% and 4%–7%, respectively, were employed to replicate in situ conditions. ICCP was applied to the tendons at two levels of polarisation, normal protection (ICCP-N) in the range of −650 to −750mV and overprotection (ICCP-O) ranging between −850 and −1300mV, both versus Ag/AgCI/0.5-M KCI for an extended period. After ICCP, the tendons were removed from the mortar and slow strain tensile tests were conducted. The results show that ICCP at both normal and overprotection had no significant influence on the elastic modulus, yield, 0.2% proof stress and ultimate strength of the tested tendons. Although ductility was reduced, fracture occurred after reaching the ultimate strength.

KEYWORDS: accidental over-polarisation; cathodic protection; ductility; toughness; ultimate strength

1. 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 [1]. 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 de-icing 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 to conventional reinforcing steel but its impact could be greater since 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 [2]. 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 which may lead to premature rupture. It has long been recognised that excessive polarisation by cathodic protection e.g. 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 [3].

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 [4, 5, 6, 7, 8].

Due to the compression of concrete in pre-stressed concrete structures, cracking is better controlled as well as enabling a reduction of the cross-sectional area of a member, 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 (LNG) 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. The tendons are then sprayed with gunite to provide a durable, smooth finish. 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 [9].

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 (cathodic protection) reinforced concrete currently suffering, or at future risk, of steel corrosion. In many cases, CP provides a practical and cost-effective solution to deal with the corrosion problem [10]. In this research, the key to a successful outcome is to ensure that the Impressed Current Cathodic Protection (ICCP) operates in a manner which reduces the risk of hydrogen embrittlement for certain sensitive grades of pre-stressed steel. The steel used in this research was a cold drawn wire with an ultimate tensile strength of approximately 1860 MPa to BS 5896 [11] and ASTM A 416, Grade 270 [12].

2. RESEARCH SIGNIFICANCE

It is well known in the infrastructure management industry that the risk of generating sufficient hydrogen during the application of cathodic protection means there are concerns over its use in pre-stressed concrete [13]. Hydrogen embrittlement can lower the fracture resistance of high-strength steels especially if over-polarised [14]. The purpose of this research is to determine the sensitivity of tendons to accidental over-protection e.g. due to poor design, maintenance and operation and in the process, determine if such an occurrence is detrimental to the performance of the steel tendons.

3. SELECTION OF APPLIED POTENTIALS

In terms of the applied ICCP potential, previous research investigated the influence of newer high strength alloys in marine applications [15, 16]. It raised concerns about under-protection, which would lead to some corrosion occurring whereas over-protection may lead to cracking in high steels susceptible to hydrogen embrittlement (HE). Hence a balance is required and it was determined that a potential within the range -770 to -790 mV (SCE) was suitable to achieve both corrosion protection and a low risk of HE.

A number of electrochemical and mechanical properties for welded high strength steel were subjected to an applied constant cathodic potential and tested using a slow strain rate test. The optimum potential region without the evolution of hydrogen embrittlement was determined between −770 and (above) −850 mV (SCE) [17]. Eliassen [18] found that for high strength pipeline steel, potential levels more negative than -800 mV vs. Ag/AgCl (along with low operating temperatures, coating failures and high hydrostatic pressures as a result of deep waters) were the most critical factors. Ishii et al [19] also found that under tensile tests with a slow strain rate, the susceptibility to hydrogen embrittlement of the prestressing wire tended to increase when the potential was more negative than -1000 mV, vs SCE.

Stress/strain tests were conducted on smooth and notched wire tendons in de-aerated $Ca(OH)_2$ solutions as a function of potential, pH, precharging time and Cl^- [20]. It was determined that the potential is the most important variable with a threshold value of −900 mV SCE being identified below which embrittlement is enhanced. Similarly, it was found elsewhere that although the hydrogen potential is not fixed due its dependency on a number of variables, a potential more positive than -900mV is generally regarded as having a low risk of hydrogen embrittlement for pre-stressed steel in concrete [21].However, there remains a fear in the industry of the risk of accidental over-protection i.e. more negative than -900 mV vs SCE which thereby restricts the application of CP for pre-stressed structures. However, there remains a fear in the industry of the risk of accidental over-protection i.e. more negative than -900 mV vs SCE which thereby restricts the application of CP for pre-stressed structures.

Isecke and Mietz [22] also investigated the risk of hydrogen embrittlement due to hydrogen evolution in the cathodic reaction, especially during the application of overprotection. It was determined that the threshold potentials in prestressed concrete structures should be less negative than -750 mV CSE, even if used on reinforcing steel, but where prestressing steel is also present, a less negative potential also reduces the risk of hydrogen assisted fracture. The risk of hydrogen embrittlement is increased if CP is directly applied to prestressing steel with potentials lower than -900 mV SCE. Regardless, it is not recommended to use CP on certain types of prestressing steel such as the quenched and tempered type.

4. EXPERIMENTAL PROGRAMME

The influence of ICCP on four batches of corroded tendons was determined in the laboratory by introducing a number of different conditions to replicate on-site situations. A summary is given in Table 1. The batch number and test code are given in cols. 1-2 in Table 1. Exposure to different degrees of corrosion to the main steel tendons to replicate increasing deterioration was also conducted, Table 1, col. 3. These were corrosion Stage I, II and III with target losses of cross-sectional area of 0-1 %, 2-4 % and 4-7 % respectively. The tendons were also pre-stressed with two different categories of pre-stress, namely Low (~ 400 MPa/~ 30 % UTS) and High (~1400 MPa/80 % UTS), col. 4, Table 1. Based on the review of applied potentials in Section 3, of the four batches of steel tendons tested, two were exposed to normal ICCP operation e.g. kept low at -650 to -750 mV vs Ag/AgCI/ 0.5M KCI (ICCP-N) and the other two at potentials considered over normal operating range e.g. -850 to -1300 mV vs Ag/AgCI/ 0.5M KCI (ICCP-O), Table 1, col. 5. Control samples were also included in each batch (no ICCP and no corrosion). ICCP was applied at the completion of accelerated corrosion whilst the specimens remained in the moulds.

4.1. Materials and Apparatus

Smooth pre-tensioned tendons, with a length of 1.4m and diameter of 5.4mm, were used in this study. The tendons used were the king wires extracted from a seven wire strand. The strands are manufactured from hot rolled 12 mm diameter rod by cold drawing through a series of dies to the finished diameter of 5.4 mm. The UTS is approximately 1860MPa.

A titanium mesh was used as the cathode when inducing corrosion to the tendons and as an anode during the application of ICCP. This was a mixed metal oxide (MMO) titanium mesh type 170 anode ribbon mesh with a width of 20 mm, Grade 1 as per ASTM B265 (23). The cement was CEM II/A-L 32.5 N Portland-limestone cement which conforms to BS EN 197-1:2011 (24) and a coarse sharp sand (50% passing a 600 μm sieve) was used for the mortar specimens. The water/cement ratio was approximately 0.4 and was based on professional judgement to replicate the consistency of gunite as used on-site. Extra pure di-ammonium hydrogen citrate was used to clean the tendon before use (and after completion of corrosion and ICCP process when removed from the specimen). A DC power supply system was used to accelerate corrosion of the tendon and apply ICCP. Reference electrode types Ag/AgCI/ 0.5M KCI Type WE100 were used to measure the potential of the tendon in the mortar via contact with the mortar face. A digital voltmeter (DVM) was used to monitor the potential which had high input impedance so that current flowing through the reference electrode did not cause disturbance or affect its potential.

Two types of vibrating wires gauges, supplied by Geosense Ltd., UK, were used to measure the pre-tensioning in the tendons and continuously measure the strain in the tendon whilst under pre-load. Strain gauges with a gauge length of 89 mm (type VWS-2010) and a strain range of 3000 microstrain (με) was used where lower strains were expected (Low level of pre-stress). Where higher strains were expected (high level of pre-stress), a vibrating wire strain gauge with a gauge length of 150mm (TYPE VWS-2000) was used with a capacity of 6000 microstrain. A dataTaker DT85 was used to record any variation to the strains in the pre-tensioned tendons throughout the monitoring process which were converted to stresses via the elastic modulus from separate stress/strain tests. A digital demec strain gauge with 300mm gauge length was also used to measure the strain (compression) in the timber pre-stressing moulds during tensioning of the tendon. This would enable net losses in pre-stress to be attributed to the tendon and not a contraction of the mould.

A hydraulic jack (RCH-121) with 12 Te capacity was supplied by Apex Hydraulics in the UK. It was used to apply different pre-determined pre-loads to the tendons. It has a hollow centre allowing the tendon to pass through it. A gripping system was devised with the use of anchor wedge grips to enable the tendon to be pre-stressed by the hydraulic jack using a hand-pump. The load was precisely applied by the use of a load cell, type C-FW 10 Te and cross referenced to strain gauge readings.

4.2. Pre-tensioned Tendons and Installation of Strain Gauges

The timber moulds were fastened to a plywood (WISA-Form) base and were used to pre-load the tendons, providing formwork for conducting accelerated corrosion and later applying ICCP in tendons immersed in mortar electrolytes. A hollow cylinder/pre-stressing jack, hand pump, anchor wedges and washers were used for pre-stressing the tendon to different levels of pre-tension, as shown in Figure 1.

The strain in the tendons was measured using vibrating wire strain gauges (VWSG) firmly attached to the tendons (Figure 1 (b)). The tensioned wire in the VWSG was electronically plucked with changes in strain being related to changes in the frequency of the wire as shown in Equation 1.

$$\Delta\mu\varepsilon = \left[\left(\frac{F_2^2}{1000}\right) - \left(\frac{F_1^2}{1000}\right)\right] \text{(Gauge Factor x Batch Factor)}$$

Equation 1

where:

$\Delta\mu\varepsilon$ = the strain change in microstrain

F_1 = datum frequency of the VWSG (Hz).

F_2 = subsequent frequency of the VWSG (Hz).

The Gauge Factor and Batch Factors are constants provided by the supplier. The change in strain (in microstrain, $\Delta\mu\varepsilon$) was obtained by subtracting the initial (datum) strain from subsequent strains. The actual stress in the tendon was obtained by multiplying the strain by the modulus of elasticity of as-received tendons. Referring to Table 2, the Batch number and Test Code are given in cols. 1 and 2 followed by the initial applied pre-stress in the tendons in col. 3. The tendons were allowed to relax for up to two days before the mortar was cast.

4.3. Preparation, Mortar Mix and Specimen Design

A total of 12 timber moulds/pre-stress beds were designed, manufactured and developed with external dimensions 675 long x 200 mm wide x 100 mm deep. The timber mould was fastened to a plywood or wisa-form base and was used for pre-loading the tendon and providing formwork for the cast mortar. Pre-stressing tendons are commonly protected with gunite in pre-load applications and this was replicated in the laboratory as a mortar and several trials were conducted to ensure that the mortar has similar performance criteria to that used on-site in terms of water/cement ratio and consistency.

With regards to the design of mortar specimens for the experimental work, each tendon was 320mm in length with a rectangular cross-section of mortar of 90 mm depth and 100 mm wide. Each mortar specimen contained one pre-tensioned tendon, 5.4 mm diameter with a UTS of around 1860 MPa.

It was determined that the gunite typically used in-situ is approximately Grade 35 N/mm^2 with a cement content of about 340 kg/m^3 and this was replicated in the laboratory. Water was added to achieve a workability similar to gunite (as is the case on-site where water is added at the nozzle) and achieve an average 28 day cube strength in accordance with BS EN 12390-3 (25) of over 35 MPa. The mortar mix proportion was cement: sand: water of 1:3:0.4.

The wet mix was then cast into the timber moulds Figure 2 (a) in layers and each layer was carefully compacted by a vibrating poker with care being taken not to disturb the tendon. The MMO mesh was also inserted into the mix, Figure 2 (b). After casting, the timber moulds were covered with polyethylene sheets and cured in the laboratory. The cast moulds were then kept moist by spraying water at 20°C for a further 27 days (28 days in total). Cube specimens were cast for each mix and tested for compressive strength in accordance with BS EN 12390-3 [25]. Cubes were tested at 1, 14, and 28 days age.

4.4. Accelerated Corrosion Technique

Impressed anodic current has been widely used to accelerate the corrosion of steel in concrete. This method has been selected for this study on the basis of it being relatively fast and the amount of corrosion generated can be calculated from the current passed using Faraday's Law. A constant current density of 1 mA/cm^2 was adopted in this investigation based on previous work carried out by the authors (9, 26, 27, 28, 29). It is accepted that this current density is much higher than would be present in a real situation but this was applied to give the appropriate level of corrosion within a reasonable timescale. At 28 days after casting the mortar, the tendon in each specimen was subjected to general corrosion by applying an anodic impressed current provided by a DC power supply, the tendon acting as the anode and MMO Ti mesh as the cathode.

Based on Faraday's Law, the degree of corrosion (as a percentage of reduction in reinforcing bar diameter) is defined by the expression $(2Rt'/D)(100)$ %, where R is the rate of corrosion in mm/year, D is the tendon bar diameter in mm, and t' is the time in years after corrosion initiation [30]. Applying a unit degree of corrosion, m = 1 %, the time taken to achieve 1 % degree of corrosion is:

$$\frac{(2)(R)(t')}{D}=\frac{m}{100} \rightarrow R=\frac{(m)(D)}{2(100)(t')} \rightarrow R=\frac{(m)(D)}{(200)(t')} \text{ and } R=1165i \rightarrow t'=\frac{(m)(D)}{(200)(1165i)}$$

Equation 2

The aim was to achieve three different degrees of corrosion (Stage I, II and III) with target losses of cross-sectional of 0-1 %, 2-4 % and 4-7 % respectively. Therefore, for Stage II corrosion, substituting say m= 3%, i=1mA/cm^2 and D=0.54 cm into Equation 2 gives:

$$t' = \frac{3\ x\ 0.54}{200\ (1.165)} = 0.00695\ years = 2.536\ days = 60.8\ hours$$

Equation 3

The length of tendon surrounded by the mortar is 32 cm. The total surface area, a, of the tendon is: $a = \pi\ x\ D\ x\ L = 17.28\ \pi\ cm^2$

Therefore, the current required for say 3% degree of corrosion per tendon is obtained from:

$I = i\ x\ a = 1\ x\ 17.28\ x\ \pi = 54.28\ mA$ per specimen Equation 4

Stage I (0-1%) was considered as a control specimen for each batch and was not corroded. Similar calculations were done for other degrees of corrosion across the two stages. The current remains constant at 54.28 *mA* (Equation 4) and corrosion period was adjusted (Equation 3) to give the required degree of corrosion.

Upon completion of the corrosion and ICCP periods, the tendons were removed from the mortar, initially cleaned using a soft wire brush to remove loose corrosion products and mortar before submersing in di-ammonium hydrogen citrate for thorough cleaning. A visual inspection confirmed that the corrosion was general as opposed to pitting. Tendons were then re-weighed and the percentage loss in weight was subsequently calculated which gave the actual degree of corrosion. This is given in Table 2, cols. 4 and 5.

4.5. Impressed Current Cathodic Protection (ICCP)

4.5.1 ICCP with Hydrogen Embrittlement

ICCP can lead to hydrogen embrittlement of steel reinforcement in concrete, notably high strength pre-stressed steel, given that it is sufficiently cathodically polarized to very negative values. For steel in concrete, the predominant cathodic reaction is normally the reduction of O_2, however, a second cathodic reaction may occur involving the reduction of water, provided the potential is lowered below the hydrogen potential [31].

$$H_2O + e^- \rightarrow H_{ads} + OH^- \quad (5)$$

The adsorbed hydrogen atoms can further react to produce hydrogen gas or may dissolve into the metal:

$$H_{ads} + HH_{ads} \rightarrow H_2 \quad (6)$$

$$H_{ads} \rightarrow H_{dis} \quad (7)$$

The atomic hydrogen formed can either combine to form hydrogen gas or can ingress into the steel and can adversely influence its mechanical properties leading to brittle fracture, with higher-strength steel being more susceptible to this form of failure [31]. However, further information on the ingress of hydrogen in given in Section 5.3.3.

4.5.2 Application of ICCP

The main principle of cathodic protection is the application of an impressed current to induce negative steel polarisation and drive the steel potentials more negative than -850 mV (SSC), where the anodic reactions are thermodynamically restrained. Under these conditions the steel will be immune to corrosion. The aim of the ICCP in this research is not only to protect the steel but also determine if and when hydrogen is generated and its effect on the tendon.

To have a better understanding of the influence of ICCP on the behaviour of the pre-corroded tendons, an extended test period was adopted. Four Batches were tested with ICCP after accelerated corrosion was applied and before demoulding the specimens. For the purpose of the research and in terms of the application of ICCP, the specimens were divided into two main categories for applying ICCP, one for normal protection where the applied potential ranged between -650 to -750 mV (SSC), the other over protection where the applied potential ranged between -850 to -1300 mV (SSC). The normal range was selected based on the practical application of ICCP and the findings in Section 3, the over protection was selected to determine the impact of accidental over protection.

After completing the accelerated corrosion process by achieving the required period to reach to the target degree of corrosion, the ICCP process was commenced, replicating the real situation in the field. The tendon was connected to the negative terminal of the DC power supply to act as a cathode and the titanium mesh connected to the positive terminal to act as an anode. Before starting the test, a datum reading (rest potential) was taken. The test process and monitoring is conducted in accordance with BS EN ISO 12696:2016 [32] and the Concrete Society Technical Report No.73 [33] including instant-off readings to confirm that ICCP was being achieved. The criterion of a -100 to -150 mV potential shift is the most widely recognised criterion to ensure adequate protection from a CP system. This criterion specifies that when the CP system is switched off, the instant-off potential (E_{off}), measured at a time between 0.1 and 1 second, and the potential measured after a certain period of time, e.g. 4 to 24 hours should be between -100 and -150 mV. ICCP was applied for each specimen by connecting the pre-tensioned tendon to the negative terminal and the mixed metal oxide (MMO) titanium mesh ribbon anode to the positive terminal of a D.C power supply. The length of each tendon exposed is 32 cm.

The ICCP system operated in a stable environment of average 20 °C and humidity 60 % ± 5 %. In general, there are two methods of controlling ICCP systems. One is that the output voltage is kept constant and the current is allowed to alter in order to maintain the set potential. The other method is to fix the current and allow the potential to float. In this research, the commonly employed former system of fixed potential was employed. A power supply with a high DC voltage (60 V) was required to provide a high potential for the application of ICCP-O. The ICCP application per tendon and duration is given in Table 2, cols. 6 and 7.

4.6. Tensile Test

Tensile testing was conducted to obtain information about the mechanical properties of the tendons including ultimate tensile strength, yield strength and ductility of the material. An ESH 600 machine with load capacity 600 kN and an Epsilon extensometer (50 mm) were used to perform the stress/strain tests to destruction. All tests were conducted in accordance with BS EN ISO 6892-1:2016 with a slow strain rate of 0.00025/sec [34].

Upon the completion of the test, the tensile strength, elastic modulus, 0.2 % proof strength, toughness, ductility and elongation were calculated. An explanation of the toughness calculation is given in Section 0 whereas information on the ductility calculation is given in Section 0. In order to determine elongation, the test specimen is re-joined to measure the final length and compared to the original length. The original cross section measurement is also compared to the final cross section to obtain the reduction in area.

5. RESULTS AND DISCUSSION

In order to reflect actual practice, the pre-tensioned tendons were subjected to corrosion followed by the application of ICCP. It would also have been useful to investigate the performance of the tendons immediately after the corrosion period so any effects solely due to corrosion could have been isolated from the combined results. However, in order to maximise the data reflecting actual practice, testing was done as described.

5.1. Instant-Off (E_{off}) Potential of the Tendons

The Instant-Off (E_{off}) is an important parameter with regards to the potential of the tendons during the application of ICCP. E_{off} was measured throughout the period of ICCP application (using recommendations from 32, 33). In addition to measuring E_{off}, the monitoring period also included:

- measuring the applied current (range 4 - 32 mA) and voltage (range 1.62 - 4 V) for ICCP-N. For ICCP-O the applied current ranged from 14 - 38 mA and the voltage ranged from 56 – 60 V
- recording the potential using surface reference electrodes (Ag/AgCl/KCl 0.5M)
- applying depolarisation (Instant-Off) for each reading and potential decay for 24 hours in two to three month intervals
- checking the applied service stress via the datalogger strain readings
- close visual inspection of the surface of the mortar and recording any change

The rest potential E_{corr} vs. SSC of the tendons when no cathodic protection was applied ranged between -513 mV to -670 mV vs. SSC.

E_{off} for the tendons with High levels of pre-stress under the application of ICCP-N is shown in Figure 3 (Batch 2). After around 150 days the potential for both Stage II and III corrosion becomes less negative and generally steadier thereafter, with Stage II corrosion showing less negative potentials throughout. The general trend for E_{off} for the Low level of pre-stress (Batch 1) generally followed that of the High level but is not shown in Figure 3 for clarity.

Figure 4 shows E_{off} for the tendons under the application of ICCP-O for corrosion Stages II and III for the High level of tendon pre-stress (Batch 4). The general trends for E_{off} with Stages II and III corrosion are broadly similar. After about 50 days the potential became less negative and relatively steadier. Similar to Figure 3, the Stage II corrosion exhibited slightly less negative potentials. This trend was generally repeated for the Low level of pre-stressed tendons (not shown in Figure 4).

5.2. Effectiveness of ICCP - Potential Decay

Based on CP criteria, the potential decay or the potential shift (ΔE_{off}) is the difference between instant-off (E_{off}) and the potential after a period of between 4 to 24 hours. The effectiveness of ICCP was examined by conducting a potential decay test, with the ICCP interrupted for 24 hours before it was switched on again. This potential decay was monitored, recorded and plotted in Figure 5 for the tendons under the application of ICCP-N and Figure 6 shows the potential decay for the tendons under the application of ICCP-O. Based on the data collected, the potential decays were more than 100 mV after 4 hours for all monitoring events. According to the Concrete Society Technical Report No 73 [33], this demonstrates that an adequate level of cathodic protection has been achieved.

5.3. Influence of ICCP on Mechanical Properties of Pre-tensioned Tendons

The impact of cathodic protection on the tendons was determined via a series of slow strain tensile tests conducted on both randomly selected as-received samples and those where ICCP-N and ICCP-O was completed. The tensile tests were conducted in accordance with BS EN ISO 6892-1:2016 [34] with results compared in the following sections.

5.3.1. Mechanical Properties of the As-received Tendons

Stress-strain curves were determined from three samples for the as-received tendons as shown in Figure 7. The elastic and plastic stages are clearly shown and the mechanical properties are almost identical for each type of tendon. These stress-strain curves indicate that the tendons are a ductile steel with high tensile strength with very similar characteristics.

The key mechanical properties determined from Figure 7 are presented in Table 3. Referring to Table 3, the Test Code is given in col. 1 and the mean diameter in col. 2. Cols. 3-7 show the proof strength, tensile strength, Young's modulus, elongation and breaking strength respectively. The majority of the data shows good repeatability with average original diameter of the tendons being 5.32 mm, the average proof strength is 1720 MPa, the ultimate tensile strength is 1979 MPa. The elongation was the property with most variation, ranging from 1.10 % to 4.90 % with an average of 2.58 %. Young's modulus averaged 215 GPA with the average breaking strength 1520 MPa. In addition, images of the fracture modes showed a cup-cone failure mode which is characteristic of ductile steel.

5.3.2. Impact of ICCP on Tendons using Stress-Strain Curves

The stress-strain curves for the ICCP-N exposed tendons are given in Figure 8 and for the ICCP-O exposed tendons in Figure 9 (along with the stress-strain curve for the as-received tendons obtained from the average of the three curves in Figure 7). Example of the fracture surfaces showing ductile failure are also inserted into Figure 8 and Figure 9. The key data from these curves is used to determine the impact of the application of ICCP on the mechanical properties of the tendons and this is presented in Table 4. Referring to Table 4, the batch number and test code is given in cols. 1 and 2 where batches 1-2 relate to the normal protection (ICCP-N) and batches 3-4 relate to the over protection (ICCP-O). The target degree of corrosion in terms of Stage of Corrosion along with the actual degree of corrosion in terms of percentage of cross-sectional area lost is given in cols. 3-4. The ICCP period is given in col. 5 and mean original diameter is given in col. 6. Data from the stress/strain tests are given in cols. 7-13 and include the ultimate tensile strength, proof strength, elongation, necking, Young's modulus, toughness and finally, information on the failure location of the fracture respectively.

The results of the tested as-received samples (Table 3) and ICCP exposed samples (Table 4) are compared to determine the influence of cathodic protection on high strength pre-stressing tendons and these are given in Table 5 and Table 6. Referring to Table 5, the Batch number and test codes are given in cols. 1 and 2, a comparison of Young's modulus is given in col. 3, the 0.2% proof stress is given in col. 4 and ultimate tensile strength in col. 5. Table 6 has a similar col. 1 and 2 as Table 5 with a comparison of elongation given in col. 3, toughness in col. 4 and ductility in col. 5. The following sections provide information of the influence of ICCP on the aforementioned six key mechanical properties of pre-stressing tendons.

Young's Modulus: The comparison in Young's modulus between the as-received and ICCP exposed tendons is given in Table 5, col. 3. For Batch 1, Young's modulus ranges between 213 to 220 MPa and for Batch 2 it was between 205 and 212 MPa. ICCP-N appears to have no effect in the elastic stage properties of these tendons. For Batch 3, Young's Modulus ranged between 205 to 214 MPa, whereas Batch 4 was ranged between 210 to 213 MPa. ICCP-O, therefore, as was the case with ICCP-N shows only minor variation in the elastic properties of these tendons compared to the as-received samples which averaged 215 GPa. The largest difference was 10 MPa (215 to 205 GPa) or 5 %.

This variation does not pose a great issue, in the UK for example, for any pre-stressed wires used in bridges, the Design Manual for Roads and Bridges document CS 455 [35] which relates to the assessment of concrete highway bridges and structures specifies the short term elastic modulus to be taken as 200 GPa based on BS 5896 [11] if test results are unavailable. Therefore, the elastic modulus remains above the minimum value determined after exposure to ICCP.

*0.2% Proof Strength:*Proof strength of the tendons was generally unaffected (either Low or High pre-stress) by the application of ICCP-N, the maximum difference being ± 2 % as shown in Table 5, col. 4, Batch 1 and 2. With regards ICCP-O, the Low level of pre-stress exhibited a maximum loss of - 6.5% for tendon 3 of Batch 3, whereas the High level pre-stressed tendons all exhibited a slight increase compared to the as-received, Table 5, Batch 4, col. 4.

Based on these results, the ICCP-N, in particular, has a low impact on the 0.2 % proof strength of the tendons and this would be the potential if applied in-service.

Ultimate Tensile Strength: There was no significant reduction in tensile strength for the ungalvanized tendons exposed to the ICCP-N, Table 5, col. 5. The tensile strength losses did not exceed 1 % for all tendons except for tendon 3 (Batch 2) with High Level of pre-stress and Stage III corrosion, a 2 % reduction in UTS was observed (or 42 MPa). For the tendons exposed to the ICCP-O Table 5, Batch 3 and 4, the tendons with Stage III corrosion in both Low and High pre-stress categories (tendons 3 of Batch 3 and 4) decreased by 6.5 % (129 MPa) and 4.2% (82 MPa). The higher strength losses are likely to be more as a result of corrosion rather than the influence of ICCP. However, if it is assumed that the working stress is approximately 2/3 of the characteristic strength [9], then these losses are unlikely to be a major cause of concern as the majority (except tendon 3 of batch 3) had a UTS still greater than the specified strength of 1860 MPa. It was determined elsewhere that the reduction in diameter due to corrosion of 1.78 mm in a 5 mm diameter tendon would lead to overstressing and possible failure of the tendon [9]. Furthermore, as the degree of corrosion increase, deeper corrosion pits will form meaning the loss in cross-sectional area to cause over-stressing will be achieved more easily. It was also determined elsewhere [28] that the application of CP can lead to a slight reduction in bond between the steel and concrete. However, in the early stages of corrosion, bond can actually increase due to the increased roughness of the steel surface [28]. Hence, the application of ICCP versus the impact of corrosion is a trade-off but likely to yield more positive outcomes as a result of a do-nothing approach where the formation of an increasing pit could be detrimental if corrosion is present.

The variation in Young's Modulus, UTS and 0.2 % proof strength is shown graphically in Figure 10 for the Low level of pre-stress and in Figure 11 for the High levels of pre-stress, both exposed to ICCP-N and ICCP-O.

Elongation: A comparison between elongation for the as-received and ICCP exposed tendons is given in Table 6, col. 3. The tendons exposed to pre-corrosion show an actual variation in elongation behaviour under ICCP-N in the range -1.1 % to 0.9 % which corresponds to a percentage difference of between -42 % to 35.4 %, Table 6, Batch 1 and 2. With regards the elongation of the tendons under the application of ICCP-O (Table 6, Batch 3 and 4), the actual elongation differences are in the range -0.1 to 2.9 % which corresponds to a percentage difference of between -3.3 to 112.8 %. According to these results, the elongation of the ungalvanised tendons exposed to ICCP-N is lower than the tendons exposed to ICCP-O compared to the as-received samples. Since elongation is a condition in the plastic region and well beyond the in-service elastic range, the negative influence of ICCP on elongation is diminished but nevertheless, is the property which exhibited most variation.

Toughness: The ability of a metal to deform plastically and to absorb energy in the process before fracture is termed toughness. The fracture energy of materials is defined by the toughness concept [36]. The toughness values of the ungalvanised tendons used in these experimental studies are given in Table 6, col. 4. According to the test results, the toughness values of tendons varied after ICCP-N application in the range 69 to 125 x 10^6 J/m^3 (for both Low and High stress levels). This decrease is in the range 28 to -29 % compared with the toughness of the as-received tendons. The variation in toughness of tendons after the application of ICCP-O was in the range 6.5 to -48.5 x 10^6 J/m^3 with Low Level and High Level of pre-stress compared with the toughness of as-received tendons (Table 6, Batch 3 and 4). This variation was more noticeable with the specimens exposed to Stage III corrosion and indicates that the behaviour of these tendons suffered from both degree of corrosion and the application of the higher potential as a result of ICCP-O.

Ductility: Ductility is a measure of the amount of plastic deformation (strain) to the fracture and this is shown in Table 6, col. 5. The data shows that the ductility percentage decreased after applying the ICCP-N was in the range 27 % to 32.3 % for the ungalvanised tendons with both Low and High level of pre-stress, Batch 1 and 2 respectively, Table 6. It was also observed that the decrease of ductility is greater with specimens exposed with Stage III corrosion, see tendons number 3 in Batch 1 and 2. This reduction in ductility appears to be caused by additional corrosion rather than the application of ICCP-N as was previously observed elsewhere [37]. For the tendons exposed to the ICCP-O (Table 6, Batch 3 and 4), results show that the ductility varied after application of ICCP-O in the range -55.6 % to 3.7 % for tendons with both Low and High levels of pre-stress. It was also observed that the variation in ductility is greater for specimens exposed to Stage III corrosion which is the same as the behaviour of tendon under the application of ICCP-N. This indicates that the ductility of tendons with higher levels of corrosion are more affected by the application of CP.

The variation in ductility properties for tendons exposed to both ICCP-N and ICCP-O is shown graphically Figure 12 and Figure 13 for Low and High levels of pre-stress respectively.

5.3.3. Risk of Hydrogen Embrittlement

The results presented in Section 5 demonstrate that the application of ICCP did not have a detrimental effect on the mechanical properties of tendons. There were some differences between the ICCP-N and ICCP-O especially in the plastic region but generally the elastic performance of the tendon in the elastic region was similar. The key concern with using cathodic protection on high strength steel is the influence of hydrogen on embrittlement. A possible reason why the high-strength tendons performed so well is that these tendons go through a rolling and drawing process in their manufacture and, thereby, introducing high compressive residual stress. It was shown elsewhere that the introduction of the high compressive residual stress delays the diffusion of hydrogen towards the inner areas of the tendon [14]. In another study [17] where the surface of welded high strength steel was exposed to hydrogen by the application of different fixed cathodic potentials, solutions of simulated carbonated concrete solutions with and without 0.1 M NaCl were used. The steel was simultaneously loaded in tension at a slow strain rate until fracture occurred. Fractographic analysis was conducted and the concentration of absorbed hydrogen was measured in the iron lattice. It was determined that penetration of the hydrogen atom only occurred when the steel was under tension and above the elastic limit, the application of CP without tensile stress did not allow the hydrogen to penetrate. It was also noted that the chloride ion present in addition to the hydrogen embrittlement did not lead to a notable synergic effect in the high-strength steel's mechanical properties. The diffused hydrogen in iron lattice did not significantly reduce the yield stress and ultimate stress but it did reduce the strain at fracture. It agreed with the theory that the cohesive energy and fracture toughness reduced as a result of hydrogen but also stated that cathodic protection can be used in aggressive media to prevent corrosion or stress corrosion cracking [13].

Therefore, the findings in this research broadly agree with other studies where it was determined that the application of cathodic protection does not necessarily lead to damage as a result of the evolution of hydrogen and possible embrittlement of the steel, even as a result of accidental over protection. A proper CP design whereby the potentials are kept low and applied to tendons steel can prevent further deterioration due to corrosion which would be preferable to the do-nothing approach where corrosion pits could be allowed to form with possible disastrous consequences.

6. CONCLUSIONS

A summary of the significant conclusions drawn from this investigation is as follows:

- There was no significant effect of either ICCP-N or ICCP-O on the strength of the tested tendons. The ultimate tensile strength and the 0.2 % proof strength for all tendons was similar. Typically, the design safety factor is set to a maximum level of stress at approximately ⅔ characteristic strength for structural engineering components. Although the ductility has been reduced by the application of the ICCP, the fracture occurred after reaching the ultimate strength in the tendons
- Both ICCP-N and ICCP-O did not affect the Young's Modulus, 0.2 % proof strength and UTS in the pre-stressed tendons. A reduction in ductility was noticed in tendons after the application of ICCP-N and ICCP-O. This reduction increased as the degree of corrosion increased. Overall, the damage to the tendons is not only due to the application of ICCP as there are other factors such as the degree of corrosion and the level of pre-stress and these appears to have greater influence than the application of ICCP
- The behaviour of stress-strain curves of all tested tendons shows that the fracture mode of the tendons is ductile. The absence of brittle failure, even though the pre-corroded tendons were exposed to the overprotection for 553 days, shows that the application of accidental over-polarisation in these tests did not lead to brittle failure

DECLARATION OF INTERESTS

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.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the sponsored of this research, the Ministry of Higher Education & Scientific Research in Libya, and support of the Materials and Engineering Research Institute, Sheffield Hallam University.

FIGURES

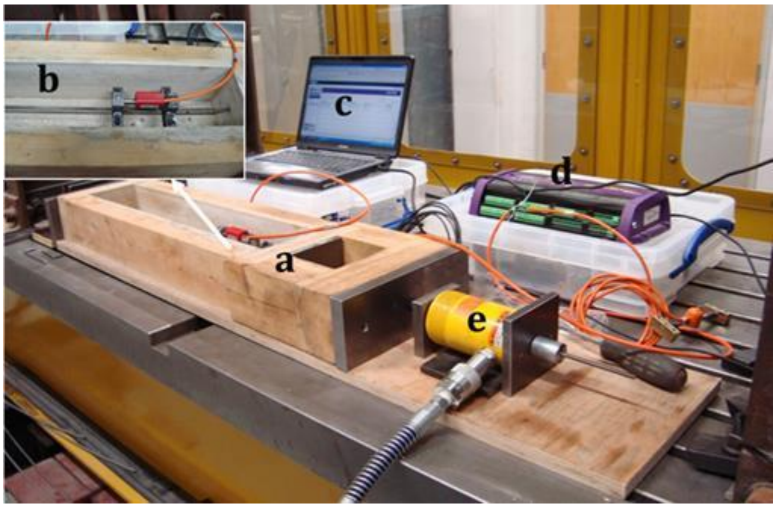


Figure 1 Pre-stressing System (a) mould; (b) strain gauge attached to pre-stressed tendon; (c) laptop; (d) data logger; (e) hydraulic jack connected to hand pump

(a) (b)

Figure 2 Preparation of the specimens: (a) casting the mortar in the mould; (b) MMO mesh inserted into the mortar

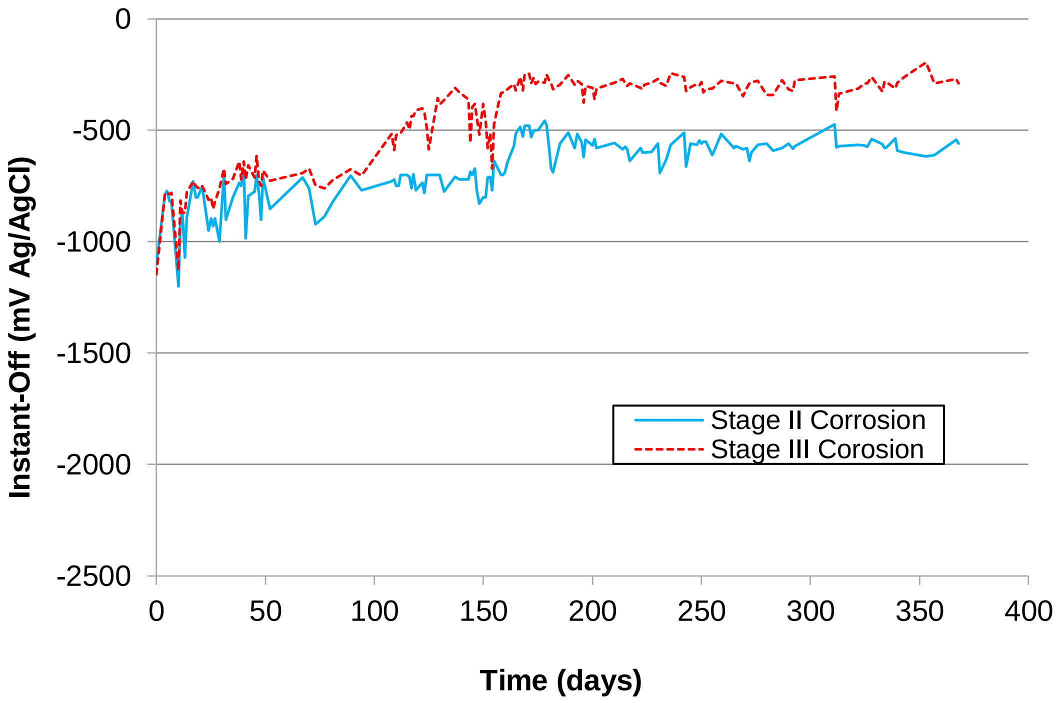


Figure 3 E_{off} for High pre-stressed tendons (Batch 2)

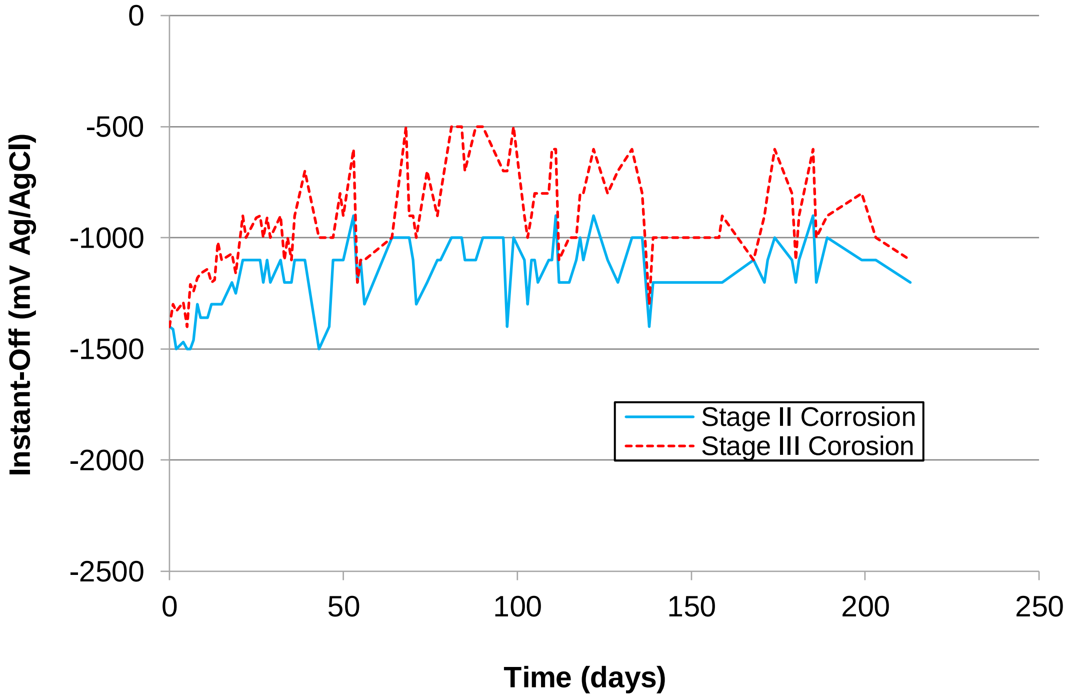


Figure 4 E_{off} for High pre-stressed tendons (Batch 4)

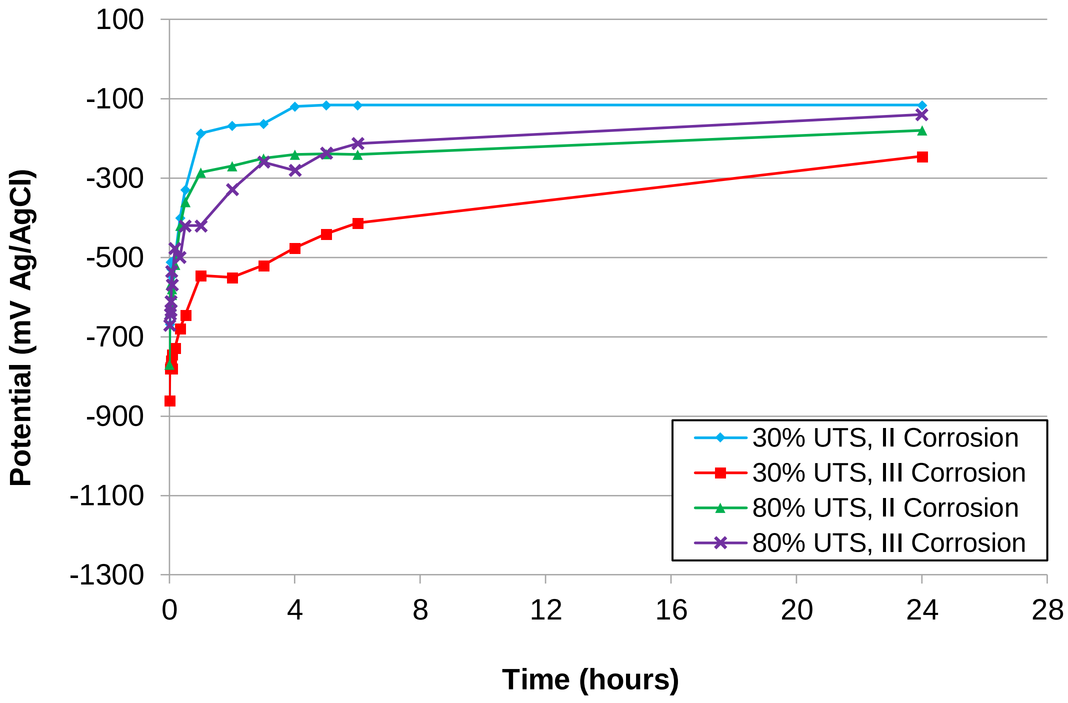


Figure 5 Potential decay of tendons, ICCP-N (Batch 1 & 2)

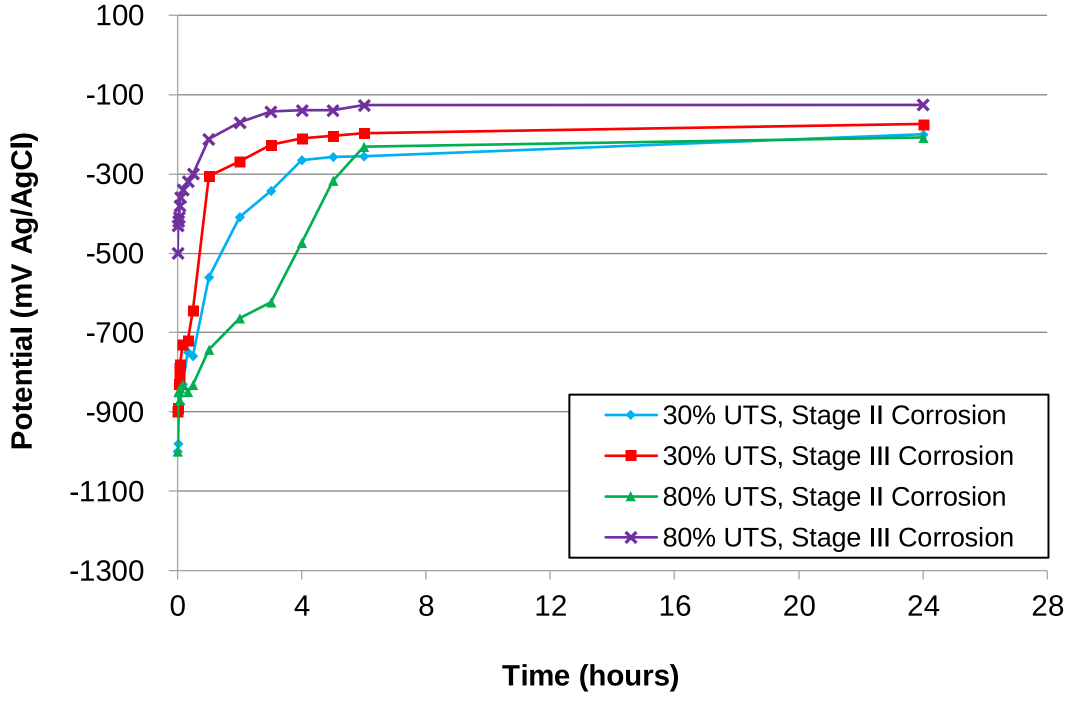


Figure 6 Potential decay of tendons, ICCP-O (Batch 3 & 4)

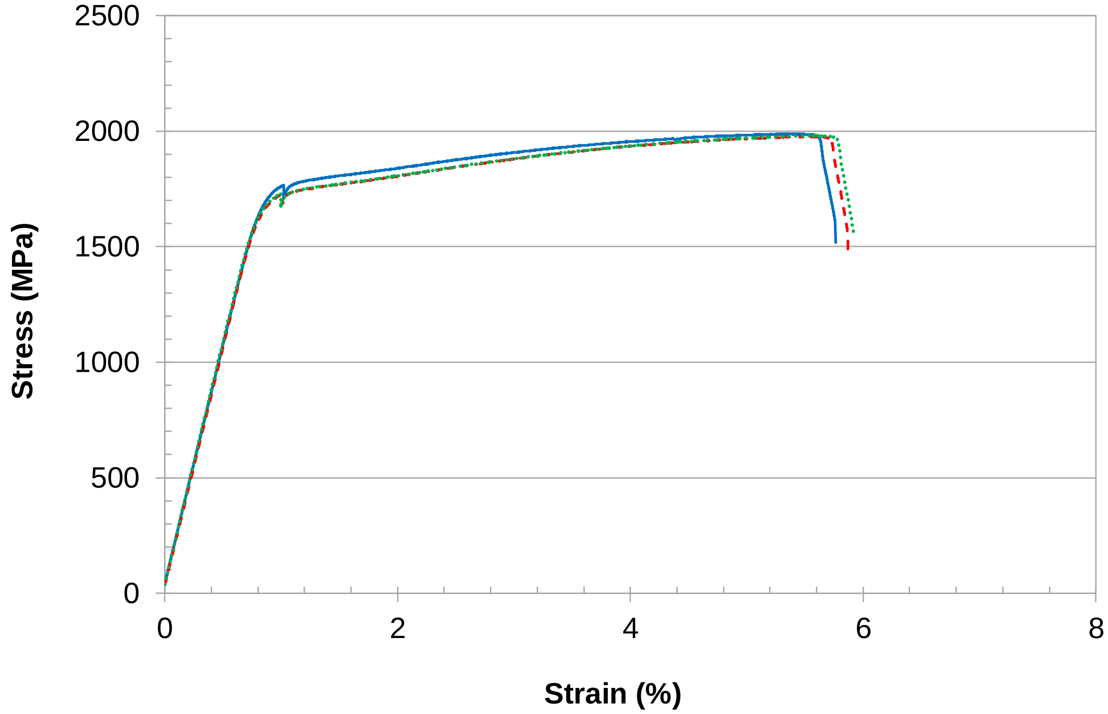
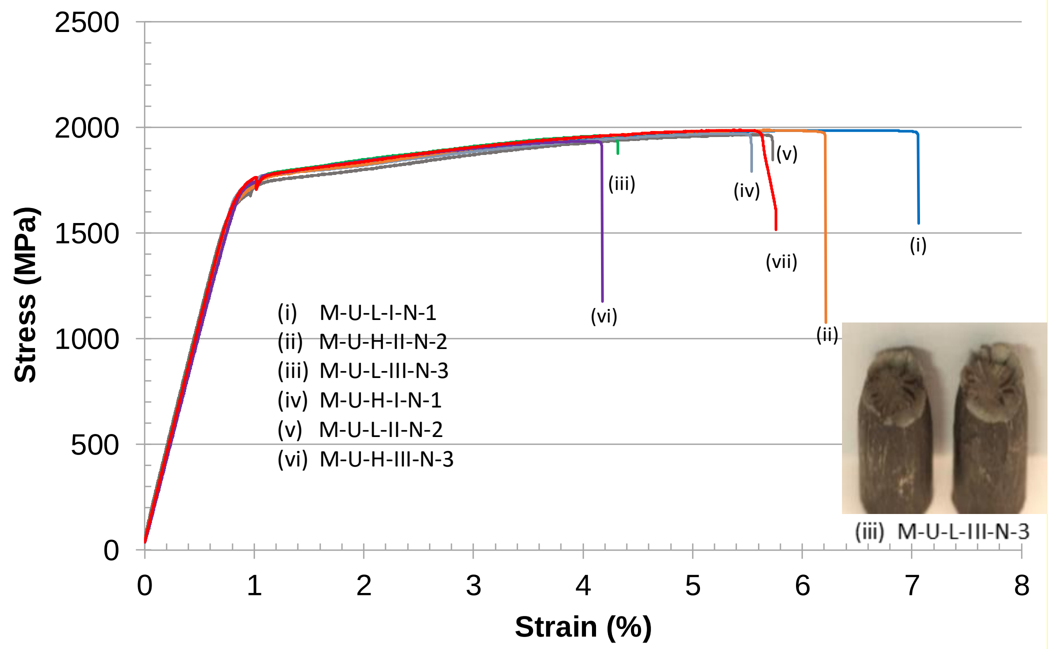
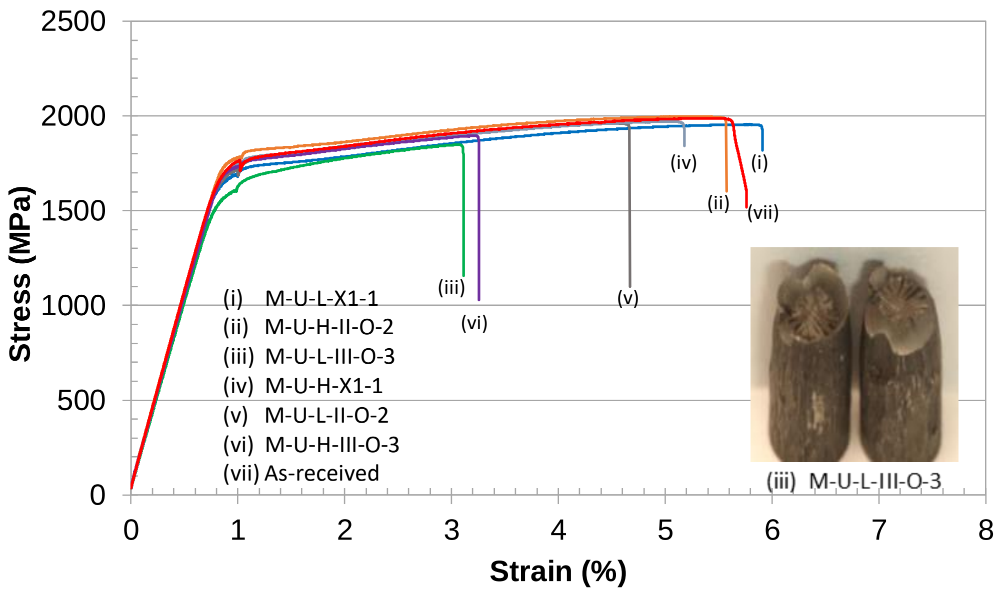


Figure 7 Stress-Strain curves for three as-received tendons



Key: M-Mortar electrolyte, U-Ungalvanised, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage II (2-4%), III-Degree of corrosion Stage III (4-7%), N-Normal protection, 1, 2, 3-Sample numbers.

Figure 8 Comparison of stress-strain curves for all tendons, ICCP-N, 30% & 80% UTS (Batch 1 & 2) with typical ductile failure mode (inset)



Key: M-Mortar electrolyte, U-Ungalvanised, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~ 80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage II (2-4%), III-Degree of corrosion Stage III (4-7%), O-Overprotection, X1- no ICCP, 1, 2, 3-Sample numbers.

Figure 9 Comparison of stress-strain curves for all tendons, ICCP-O, 30% & 80% UTS (Batch 3 & 4) with typical ductile failure mode (inset)

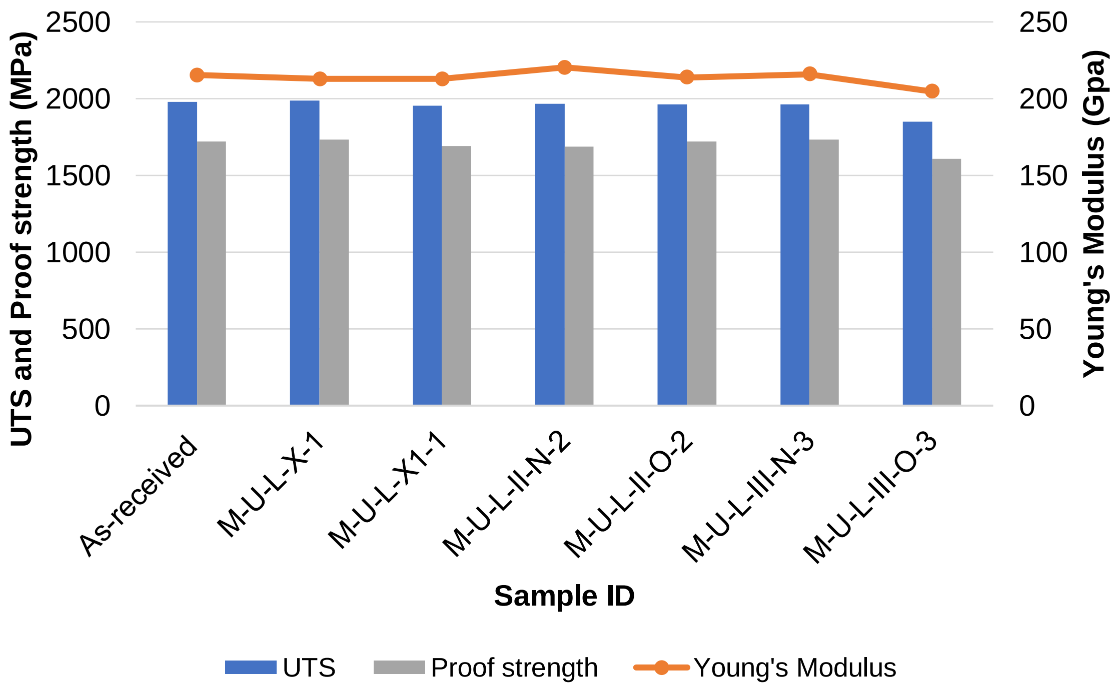


Figure 10 Comparison of mechanical properties for tendons with Low level of pre-stress for tendons exposed to ICCP-N & ICCP-O

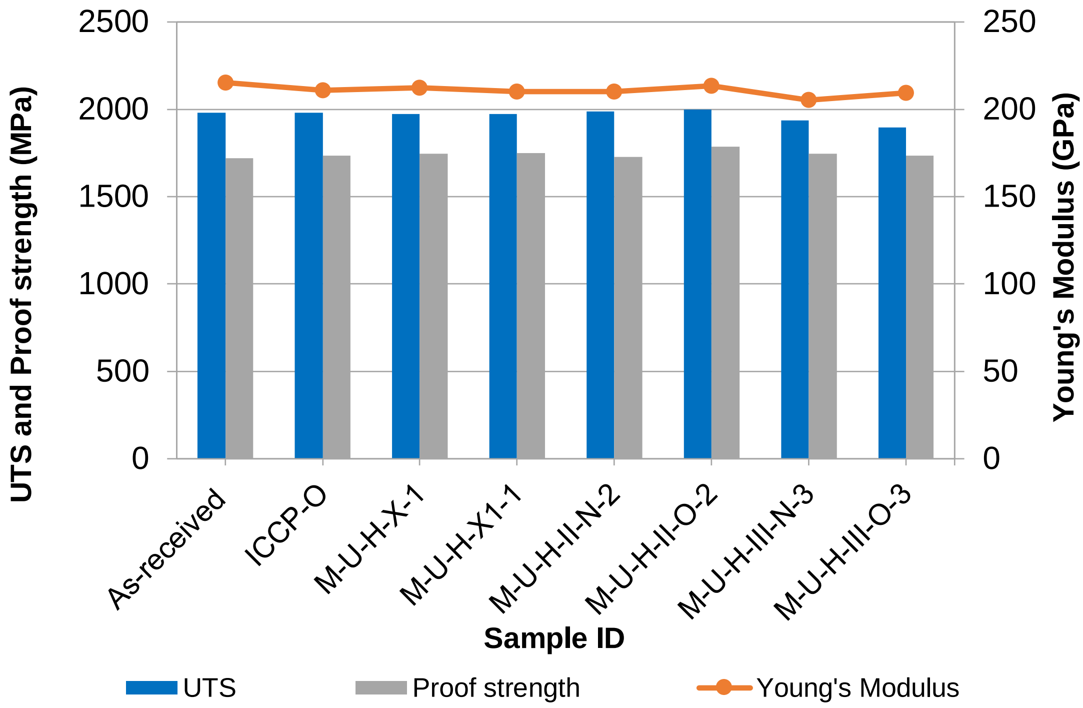


Figure 11 Comparison of mechanical properties for tendons with High Level of pre-stress exposed to ICCP-N & ICCP-O

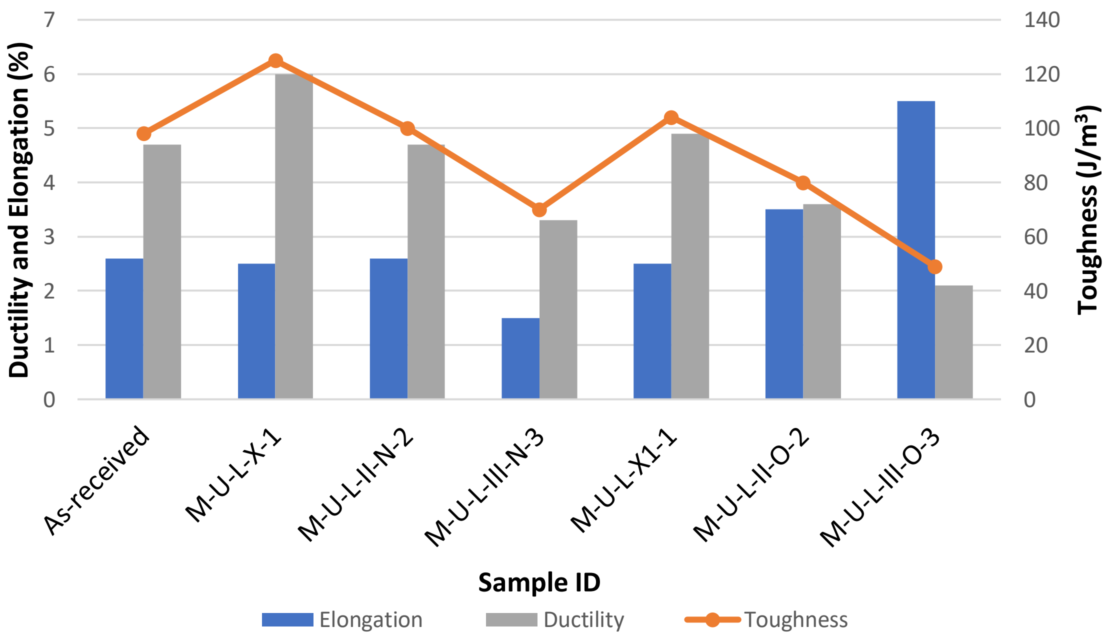


Figure 12 Comparison of ductility properties for tendons with Low level of pre-stress exposed to ICCP-N & ICCP-O

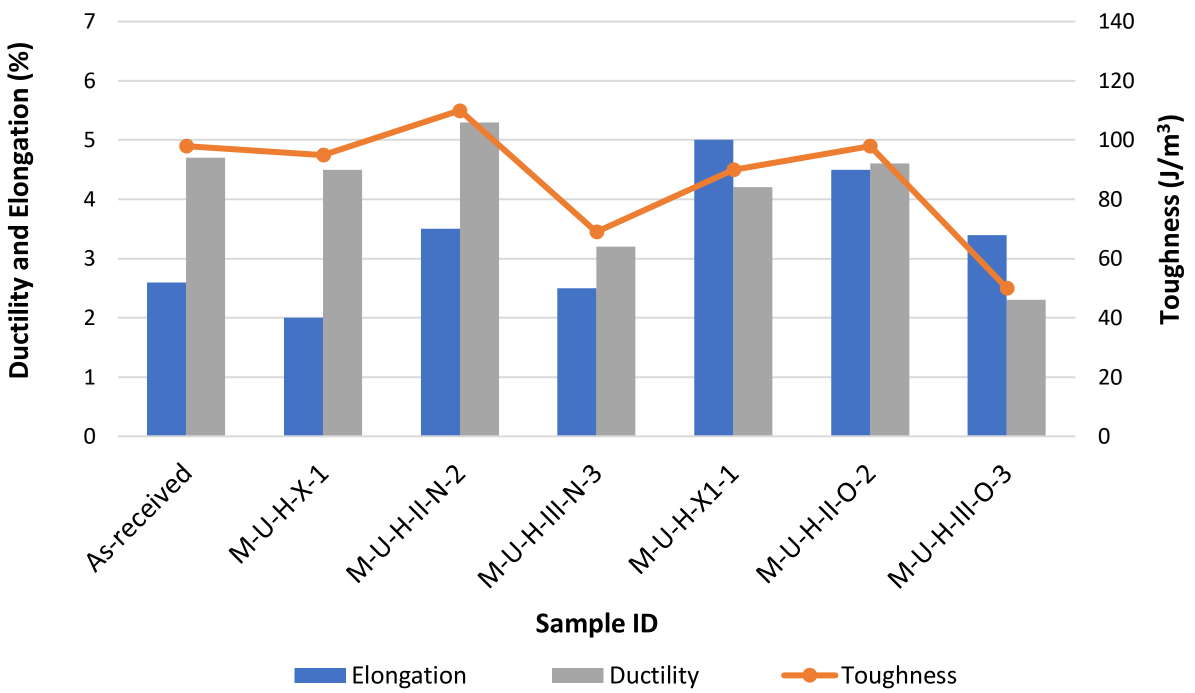


Figure 13 Comparison of ductility properties for tendons with High level of pre-stress exposed to ICCP-N & ICCP-O

TABLES

Table 1 Test Programme

1	*2*	*3*	*4*	*5*
Batch	*Test Code*	*Degree of Corrosion (Stage)*	*Level of Pre-tension*	*ICCP Application*
1	M-U-L-X-1	I	Low	None and uncorroded – Control
	M-U-L-II-N-2	II	Low	ICCP – Normal protection
	M-U-L-III-N-3	III	Low	ICCP – Normal protection
2	M-U-H-X-1	I	High	None and uncorroded – Control
	M-U-H-II-N-2	II	High	ICCP – Normal protection
	M-U-H-III-N-3	III	High	ICCP – Normal protection
3	M-U-L-X1-1	I	Low	None and uncorroded – Control
	M-U-L-II-O-2	II	Low	ICCP – Overprotection
	M-U-L-III-O-3	III	Low	ICCP – Overprotection
4	M-U-H-X1-1	I	High	None and uncorroded – Control
	M-U-H-II-O-2	II	High	ICCP – Overprotection
	M-U-H-III-O-3	III	High	ICCP – Overprotection

Key: M-Mortar electrolyte, U-Ungalvanised, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage II (2-4%), III-Degree of corrosion Stage III (4-7%), N-Normal protection, O-Overprotection, X and X1-no corrosion and no ICCP, 1, 2, 3-Sample numbers.

Table 2 Degree of corrosion and application of ICCP

1	*2*	*3*	*4*	*5*	*6*	*7*
Batch	*Test Code*	*Initial Applied Pre-tension*	*Degree of Corrosion*	*Actual Degree of Corrosion*	*ICCP Application*	*ICCP Period*
		(MPa)	*(Stage)*	*(%)*		*days*
1	M-U-L-X-1	421	I	0	None and uncorroded – Control	367
	M-U-L-II-N-2	376	II	3.98	ICCP (Normal-Protection)	367
	M-U-L-III-N-3	413	III	5.32	ICCP (Normal-Protection)	367
2	M-U-H-X-1	1136	I	0	None and uncorroded – Control	553
	M-U-H-II-N-2	1175	II	2.25	ICCP (Normal-Protection)	553
	M-U-H-III-N-3	1213	III	4.05	ICCP (Normal-Protection)	553
3	M-U-L-X1-1	359	I	0.0	None and uncorroded – Control	137
	M-U-L-II-O-2	377	II	3.96	ICCP – Overprotection	137
	M-U-L-III-O-3	412	III	6.52	ICCP – Overprotection	137
4	M-U-H-X1-1	1339	I	0.0	None and uncorroded – Control	221
	M-U-H-II-O-2	1463	II	2.06	ICCP – Overprotection	221
	M-U-H-III-O-3	1302	III	4.03	ICCP – Overprotection	221

Key: M-Mortar electrolyte, U-Ungalvanised, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage II (2-4%), III-Degree of corrosion Stage III (4-7%), N-Normal protection, O-Overprotection, X and X1-no corrosion and no ICCP, 1, 2, 3-Sample numbers.

Table 3 Tensile properties of the as-received tendons

1	*2*	*3*	*4*	*5*	*6*	*7*
Test Code	*Mean original diameter*	*Proof Strength*	*Ultimate Tensile Strength*	*Young's Modulus*	*Elongation*	*Breaking Strength*
	(mm)	*(MPa)*	*(MPa)*	*(GPa)*	*(%)*	*(MPa)*
R-1	5.33	1761	1990	214	2.22	1517
R-2	5.31	1725	1978	212	1.10	1472
R-3	5.32	1723	1982	217	2.20	1546
R-4	5.32	1718	1970	216	4.90	1524
R-5	5.30	1673	1978	216	2.50	1541
Average	5.32	1720	1979	215	2.58	1520

Key: R- As-received, 1-5 Sample Numbers

Table 4 Mechanical properties of the tendons after applying ICCP-N and ICCP-O

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Batch	*Test Code*	*Target Degree of Corrosion (Stage)*	*Actual Degree of Corrosion*	*ICCP Period*	*Mean original diameter*	*Ultimate Tensile Strength UTS*	*Proof Strength*	*Elongation*	*Necking*	*Young's Modulus*	*Toughness ($x10^6$)*	*Failure location*
			(%)	*(days)*	*(mm)*	*(MPa)*	*(MPa)*	*(%)*	*(mm^2)*	*(GPa)*	*J/m^3*	
1	M-U-L-X-1	I	0	367	5.28	1989	1733	2.5	33	213	125	T-edge
	M-U-L-II-N-2	II	3.98	367	5.34	1968	1688	2.6	29	220	100	Middle
	M-U-L-III-N-3	III	5.32	367	5.34	1963	1734	1.5	23	216	70	U-middle
2	M-U-H-X-1	I	0	553	5.35	1974	1745	2.0	27	212	95	B-edge
	M-U-H-II-N-2	II	2.25	553	5.35	1989	1726	3.5	29	210	110	U-middle
	M-U-H-III-N-3	III	4.05	553	5.36	1937	1747	2.5	32	205	69	U-middle
3	M-U-L-X1-1	I	0.0	221	5.29	1956	1690	2.5	27	213	104	T-edge
	M-U-L-II-O-2	II	3.96	221	5.34	1962	1720	3.5	24	214	80	L-middle
	M-U-L-III-O-3	III	6.52	221	5.32	1850	1608	5.5	25	205	49	Middle
4	M-U-H-X1-1	I	0.0	221	5.36	1972	1750	5.0	21	210	90	B-edge
	M-U-H-II-O-2	II	2.06	221	5.36	1998	1785	4.5	36	213	97	L-middle
	M-U-H-III-O-3	III	4.03	221	5.36	1897	1736	3.4	29	210	50	U-middle

Key: M-Mortar electrolyte, U-Ungalvanised, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage II (2-4%), III-Degree of corrosion Stage III (4-7%), N-Normal protection, O-Overprotection, X and X1-no corrosion and no ICCP, R-As-received samples, 1, 2, 3-Sample numbers, T-edge – Top edge of the grip, B-edge – Bottom edge of the grip, U-middle – Upper middle of the grip, L-middle – Lower middle of the grip

Table 5 Impact of ICCP on Young's Modulus, 0.2% Proof Strength and Ultimate Tensile Strength

1	*2*	*3*				*4*				*5*			
		Young's Modulus				*0.2% Proof Strength*				*Ultimate Tensile Strength (UTS)*			
Batch	*Test code*	*ICCP Tendons*	*As-received Ave. **	*Difference*		*ICCP Tendons*	*As-received Ave. **	*Difference*		*ICCP Tendons*	*As-received Ave. **	*Difference*	
		(MPa)	*(MPa)*	*(MPa)*	*(%)*	*(MPa)*	*(MPa)*	*(MPa)*	*(%)*	*(MPa)*	*(MPa)*	*(MPa)*	*(%)*
1	M-U-L-X-1	213	215	-2	-1	1733	1720	13	1	1989	1980	9	0
	M-U-L-II-N-2	220	215	5	2	1688	1720	-32	-2	1968	1980	-12	-1
	M-U-L-III-N-3	216	215	1	0	1734	1720	14	1	1964	1980	-16	-1
2	M-U-H-X-1	212	215	-3	-1	1745	1720	25	1	1974	1980	-6	0
	M-U-H-II-N-2	210	215	-5	-2	1726	1720	6	0	1990	1980	10	1
	M-U-H-III-N-3	205	215	-10	-5	1747	1720	27	2	1937	1980	-42	-2
3	M-U-L-X1-1	213	215	-2.5	-1.2	1690	1720	-30.0	-1.7	1956	1980	-23.4	-1.2
	M-U-L-II-O-2	214	215	-1.4	-0.7	1720	1720	0.0	0.0	1963	1980	-17.0	-0.9
	M-U-L-III-O-3	205	215	-10.7	-5.0	1608	1720	-112.0	-6.5	1850	1980	-129.5	-6.5
4	M-U-H-X1-1	210	215	-5.0	-2.3	1750	1720	30.0	1.7	1972	1980	-7.1	-0.4
	M-U-H-II-O-2	213	215	-1.9	-0.9	1785	1720	65.0	3.8	1998	1980	18.9	1.0
	M-U-H-III-O-3	210	215	-5.7	-2.7	1736	1720	16.0	0.9	1897	1980	-82.2	-4.2

Key: U-Ungalvanised, M-Mortar electrolyte, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage I (2%), III-Degree of corrosion Stage I (2-3%), N-Normal protection, O-Overprotection, X&X1-No corrosion and NO CP, 1, 2, 3-Sample numbers.
** Average of as-received tendons results*

Table 6 Impact of ICCP on Elongation, Toughness and Ductility

1	*2*	*3*				*4*				*5*			
		Elongation				*Toughness*				*Ductility*			
Batch	*Test code*	*Tested Tendons*	*As-received Ave. **	*Difference*		*Tested Tendons*	*As-received Ave. **	*Difference*		*Tested Tendons*	*As-received Ave **	*Difference*	
		(%)	*(%)*	*(%)*	*(%)*	*(J/m³) x10⁶*	*(J/m³) x10⁶*	*(J/m³) x10⁶*	*(%)*	*(%)*	*(%)*	*(%)*	*(%)*
1	M-U-L-X-1	2.5	2.6	-0.1	-3.3	125	98	28	28	6.0	4.7	1.3	27.0
	M-U-L-II-N-2	2.6	2.6	0.0	0.0	100	98	3	3	4.7	4.7	0.0	-0.5
	M-U-L-III-N-3	1.5	2.6	-1.1	-42.0	70	98	-28	-28	3.3	4.7	-1.4	-30.2
2	M-U-H-X-1	2.0	2.6	-0.6	-22.6	95	98	-3	-3	4.5	4.7	-0.2	-4.8
	M-U-H-II-N-2	3.5	2.6	0.9	35.4	110	98	13	13	5.3	4.7	0.5	11.1
	M-U-H-III-N-3	2.5	2.6	-0.1	-3.3	69	98	-29	-29	3.2	4.7	-1.5	-32.3
3	M-U-L-X1-1	2.5	2.6	-0.1	-3.3	104	98	6.5	6.7	4.9	4.7	0.2	3.7
	M-U-L-II-O-2	3.5	2.6	0.9	35.4	80	98	-17.5	-17.9	3.6	4.7	-1.1	-23.8
	M-U-L-III-O-3	5.5	2.6	2.9	112.8	49	98	-48.5	-49.7	2.1	4.7	-2.6	-55.6
4	M-U-H-X1-1	5.0	2.6	2.4	93.5	90	98	-7.5	-7.7	4.2	4.7	-0.5	-11.1
	M-U-H-II-O-2	4.5	2.6	1.9	74.1	98	98	0.0	0.0	4.6	4.7	-0.1	-2.6
	M-U-H-III-O-3	3.4	2.6	0.8	31.6	50	98	-47.5	-48.7	2.3	4.7	-2.5	-52.4

Key: U-Ungalvanised, M-Mortar electrolyte, L-Low level of pre-stress (~30 % UTS), H-High level of pre-stress (~80 % UTS), I-Degree of corrosion Stage I (0-1%), II-Degree of corrosion Stage I (2%), III-Degree of corrosion Stage I (2-3%), N-Normal protection, O-Overprotection, X&X1-No corrosion and NO CP, 1, 2, 3-Sample numbers.
** Average of as-received tendons results*

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