

**The effect of voids on the corrosion of post-tensioning
tendons: Second destructive examination**

by M McKenzie

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TRL Limited



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**THE EFFECT OF VOIDS ON THE CORROSION OF POST
TENSIONING TENDONS: SECOND DESTRUCTIVE EXAMINATION**

Version: 1

by M McKenzie (TRL Limited)

Prepared for:

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Executive summary

Post-tensioning is a common form of construction for medium to long-span concrete bridges. After tensioning, the ducts are usually filled with a cementitious grout to provide a structural bond between the stressed tendons and the concrete, and to protect the tendons against corrosion. However there is a possibility that some parts of the duct will remain ungrouted. The extent of such voids can range from a complete lack of grout in sections of the duct to regions where tendons remain partially exposed or only have a low cover of grout. If voids or exposed tendons remain dry then this should not pose a major problem. However should water get into such voids then corrosion of the tendons is likely to occur. It would be useful to have estimates of the likely rates of tendon corrosion depending on the type of void and the environment within it. This would assist in the development of models for assessing both the time at which deterioration was likely to start – important for planning inspection programmes – and subsequent rates of corrosion.

An investigation was carried out to provide information on corrosion rates for post tensioning tendons in post tensioning ducts with a range of void types. The main part of the experiment comprised a support beam with a stressed tendon running along each side. Along each tendon were sections of grouted duct with the following types of void:

Centre void where the tendon is completely exposed between two grouted zones

Ungrouted section with the tendon bare along half its length and only a grout wash along the rest of the tendon

Grouted half way up the tendon along the length of the tendon with and without chloride in the grout

Low grout cover along the length of the tendon with and without gaps to expose small areas of tendon.

The voids were filled with chloride solution or, where there was already chloride in the grout, just water to encourage corrosion. The development of corrosion was monitored visually, by electrochemical testing, and destructive examination.

There were also some smaller individual sections of ducting where the tendons were not stressed. The voids in these were the same as in the main part of the experiment.

The first destructive examination was carried out after two years exposure. This showed that corrosion was active both on the outside and within the body of the tendon. The most severe corrosion represented about 10% loss in cross-sectional area on a single wire. A second destructive examination of the remaining specimens was carried out after three years. The most severe corrosion was in the same location as before (a bare section of tendon between two grouted zones) but now represented about 20% loss in section on all the exterior wires of the tendon

Corrosion on the unstressed tendons was similar in type to that found on the stressed tendons. This supports the use of unstressed specimens, which are much easier to deal with, in any further investigations of the effects of voids in post tensioning ducts on the corrosion of the tendons.

1 Introduction

Post tensioning is a common form of construction for medium to long-span concrete bridges. The structural element (for example a bridge deck) is cast, or assembled with precast units, with preformed ducts through which steel tendons are threaded and stressed. The ducts are usually metal or plastic tubes but in some cases can be unlined. After tensioning, the ducts are usually filled with a cementitious grout to provide a structural bond between the stressed tendons and the concrete, and to protect the tendons against corrosion. Ensuring that all the tendons are protected by grout can be problematical. The grout is usually pumped into the ducting and often has to travel long distances. There is the potential for sections to remain ungrouted, and the extent of such voids can range from a complete lack of grout in sections of the duct to regions where tendons remain partially exposed or only have a low cover of grout. If water gets into such voids then corrosion of the tendons is likely to occur. This will be most serious if the water is contaminated with chlorides either from a marine location or deicing salt. Corrosion in post tensioning tendons is of particular concern as loss in section of the stressed wires could result in wire breaks and loss of structural integrity. The fact that the tendons are enclosed in ducts makes detection of deterioration difficult.

The severity of corrosion in post tensioning has been assessed by direct examination but this is a difficult and expensive process. The limited information obtained makes it difficult to decide the extent and likely future development of the corrosion. Such considerations are crucial for the future management of any deteriorating structure – in particular the timing of any remedial measures. The main problem is that the investigations provide a snapshot of the position at the time of the investigation; it is generally difficult to estimate whether the current corrosion is the result of long term deterioration possibly over the whole life of the structure, or the result of a much shorter period of corrosion resulting from a specific change in environment – say the breakdown of a waterproofing system. Even with measurements at more than one time there is generally insufficient information to enable corrosion rates to be estimated with any confidence. It would be useful to have estimates of the rates of corrosion under the varying conditions likely to exist in a post tensioned structure. This would assist in the development of models for assessing both the time at which deterioration was likely to start – important for planning inspection programmes – and likely subsequent rates of corrosion. Development of deterioration models is of particular interest when there are a number of remedial treatments available and the most cost effective solution is sought.

To provide more comprehensive information on likely corrosion rates for post tensioning tendons under varying conditions, a laboratory investigation was carried out. Only a limited number of the many possible variables that might affect the corrosion could be investigated so it was decided to concentrate on conditions where corrosion was likely to be severe. The experiment was designed to estimate rates of corrosion in partially voided ducts subject to chloride contamination. The work was carried out in a number of phases. The first phase involved setting up a test rig containing stressed tendons subject to a range of corrosive conditions, supplemented by some smaller unstressed specimens. This has been reported previously (McKenzie 2004). The second phase involved monitoring the development of corrosion by electrochemical testing and visual examination over the following year; this was reported in McKenzie (2005). The third stage involved a further years exposure and monitoring followed by a destructive examination of one set of tendons to give estimates of the extent and severity of corrosion; this was reported in Mckenzie (2006). A further destructive examination was carried out after a further years exposure. This is the subject of the current report.

The design and construction of the stressed and unstressed specimens was described in detail in McKenzie (2004). Only a brief summary of the specimens will be given in this report.

2 Stressed specimens

2.1 Experimental set-up

The stressed specimen rig consisted of a steel I beam about 5 m long by 200 mm square. A single stressed tendon ran along each side of the beam midway between the top and bottom flange and offset from the web. The tendon was secured by collets at plates welded to each end of the beam. A single Superstrand tendon (nominal diameter 12.9 mm) comprising six wires spirally wound around a central straight wire was used. This had an ultimate tensile strength of about 2000 N/mm². Each tendon was stressed to around 70% of ultimate resulting in 99 kN in each tendon. Along each tendon there were five separate sections of grouted ducting containing a range of void types.

2.2 Types of void

The grout used for the experiment was a simple water/cement mixture with no additives other than sodium chloride in some sections (2% chloride by weight of cement) to encourage corrosion. The water – cement ratio was 0.45.

The following types of void were created:

Centre void where the tendon was completely exposed between two grouted zones (2 sections)

UngROUTED section with the tendon bare along half its length and only a grout wash (thin coating of grout from pouring grout over the tendon) along the rest of the tendon

Grouted half way up the tendon along the length of the tendon (2 sections)

Grouted half way up the tendon along the length of the tendon: chloride in the grout (2 sections)

Low grout cover along the length of the tendon (2 sections)

Low grout cover along the length of the tendon but with narrow gaps down to tendon level at 3 positions along the tendon

The two sides of the stressed beam were designated as T1 OUTSIDE AND T1 INSIDE. The types of void and their position along each side of the beam are shown schematically in Figure 1.

Figure 2 shows the beam after grouting of all sections had been completed. Figure 3 shows examples of particular sections.

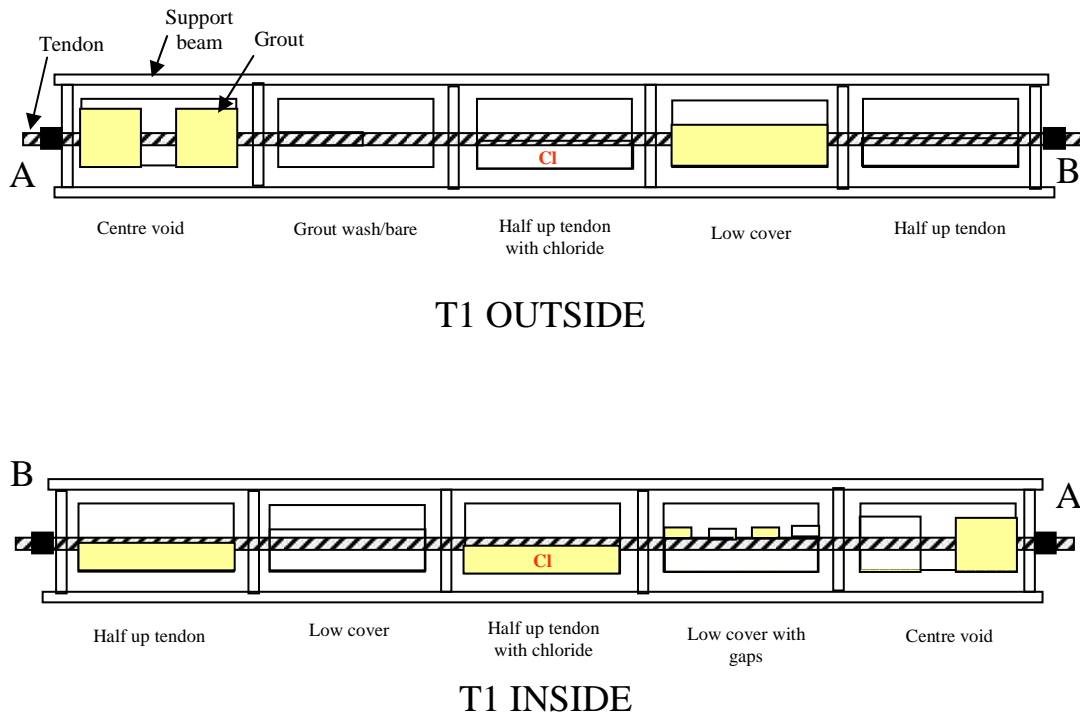


Figure 1 Layout and type of void on stressed tendons



Figure 2 Stressed specimen rig

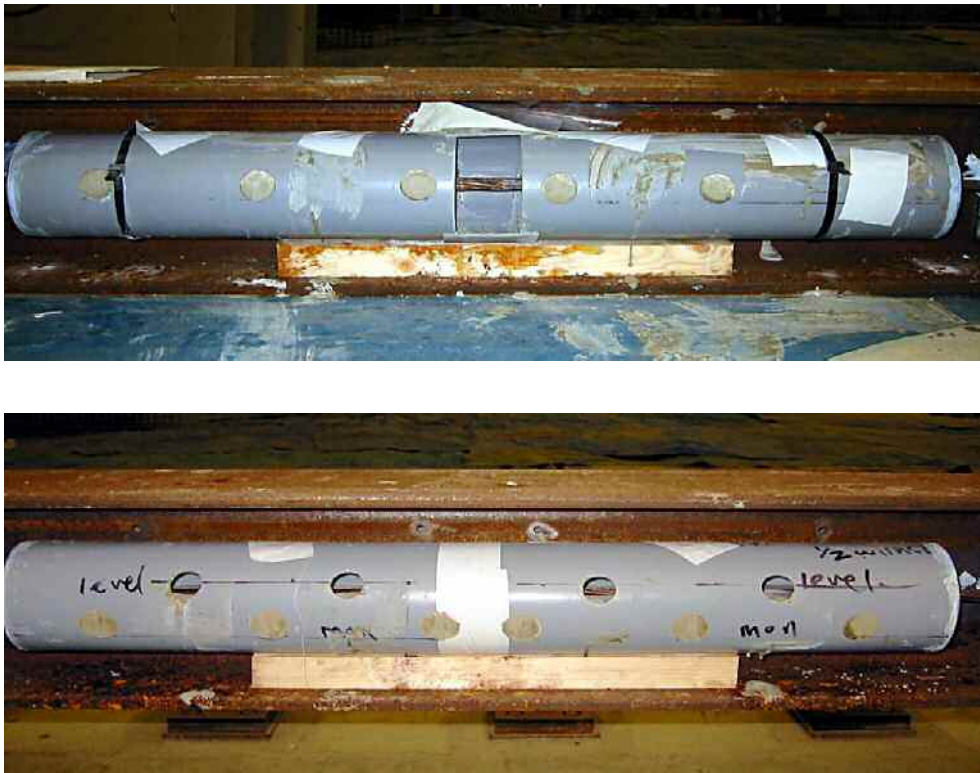


Figure 3 Sections with centre void (upper) and grout half way up the tendon (lower)

3 Unstressed specimens

Ten individual unstressed specimens were prepared using transparent acrylic tubing with a central tendon. The ends of each specimen were sealed with a rubber bung and non corrosive silicone sealant. The specimens were smaller than the stressed sections being 330 mm long and 40 mm in diameter. Grout composition and chloride content were the same as used in the stressed specimens. The voids created were similar to those in the stressed specimen rig. Note one specimen (X) was prepared at a later date than the other specimens and exposure to sodium chloride solution started about six months after the other specimens.

The types of specimen are shown schematically in Figure 4

Examples of some of the completed specimens are shown in Figure 5

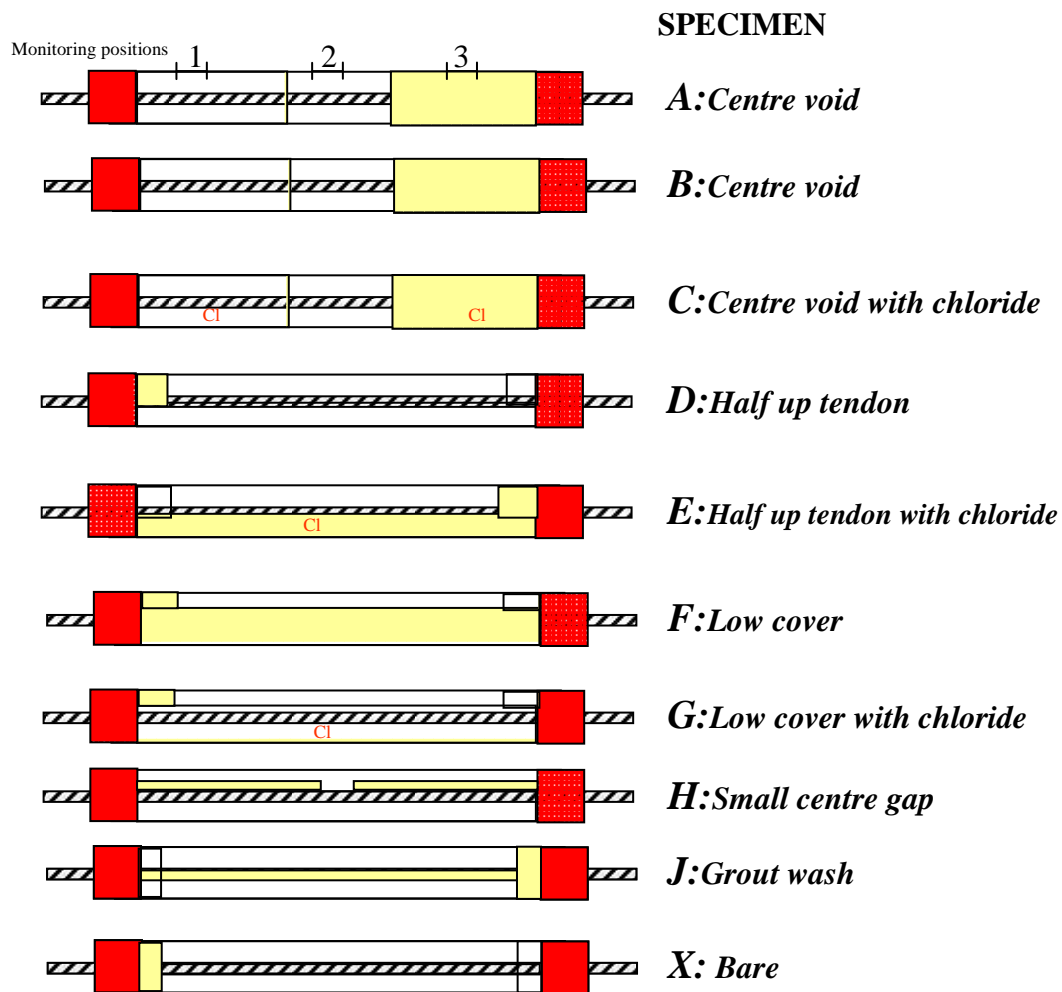


Figure 4 Types of void in unstressed specimens



Figure 5 Examples of unstressed specimens: centre void (upper), grout halfway up the tendon (lower)

4 Test conditions and routine monitoring

The stressed tendon rig was exposed in the PTF building at TRL; this is enclosed but unheated so the temperature and humidity were recorded hourly using a data logger.

The grout was allowed to cure for two months whilst initial half cell potential measurements (using a calomel reference cell) were taken of the steel in the grouted sections using the monitoring access holes in the ducting. Following these initial measurements, liquid was introduced into the voids in the sections to encourage corrosion and further measurements of half cell potential taken periodically over the exposure period. For sections where chloride had been added to the grout mix, only tap water was introduced into the voids. For sections where chloride had not been added to the mix the liquid used was a 3% solution of sodium chloride. Liquid was added so that any exposed tendon or low cover of grout was immersed. Leakage through the inspection/monitoring holes was prevented using waterproof tape; other holes in the ducting (e.g. filling holes) were also sealed using waterproof tape. Some leakage was apparent coming from between the tendon wires outside the specimen. Even when stressed together liquid can penetrate between the individual wires. Liquid was topped up each month. As conditions were not controlled the amount of liquid in the voids varied as it was absorbed or evaporated. For example in the centre void specimen, the exposed tendon went from being fully immersed at the start of the month to fully exposed by the end - the rate of change varying with the environmental conditions.

The smaller unstressed specimens were treated in a similar manner to the stressed specimens. However these were exposed in a laboratory atmosphere where the temperature was not controlled but was typically 20°C with a RH of about 50%.

5 Destructive examination

5.1 Stressed specimens

After two years exposure a destructive examination of some of the tendon segments was carried out to assess the extent and severity of corrosion. The tendon running along one side of the stressed specimen test rig (side T1 OUTSIDE) was de-stressed by applying tension to the tendon so that the collet holding the tendon in place could be removed; the tension was then relaxed. This proved quite straightforward to do and did not affect the stressed tendon on the other side of the support beam. Each individual test segment was then cut from the tendon and the plastic tubing removed.

Grout was removed from around the tendon segments by careful use of a hammer and chisel. This proved straightforward as the grout was quite brittle. The extent and severity of corrosion on the tendon segments were assessed visually. Smaller sections of tendon (approximately 200mm long) were then cut out of each tendon segment and the individual wires forming the tendon were separated. To give a clearer impression of the degree of metal loss, corrosion products on these wires were then removed using hydrochloric acid containing hexamine inhibitor to prevent dissolution of the steel..

A destructive examination of the remaining tendon T1 Inside (the main subject of the current report) was carried out in a similar fashion after three years exposure.

5.2 Unstressed specimens

One unstressed specimen was examined after two years exposure – Specimen A consisting of a grouted specimen with a centre void. The acrylic tubing was removed and the examination of the tendon carried out in the same way as for the stressed specimens.

The remaining unstressed specimens were examined in a similar fashion after three years exposure.

6 Results

6.1 Routine monitoring

6.1.1 PTF conditions

During the third year of exposure conditions varied in a similar fashion to what had been observed in previous years. Temperature varied considerably ranging from highs of over 35°C to lows of -5°C (Figure 6). Humidity ranged from 100% down to 30% but was generally high for at least part of most days (Figure 7).

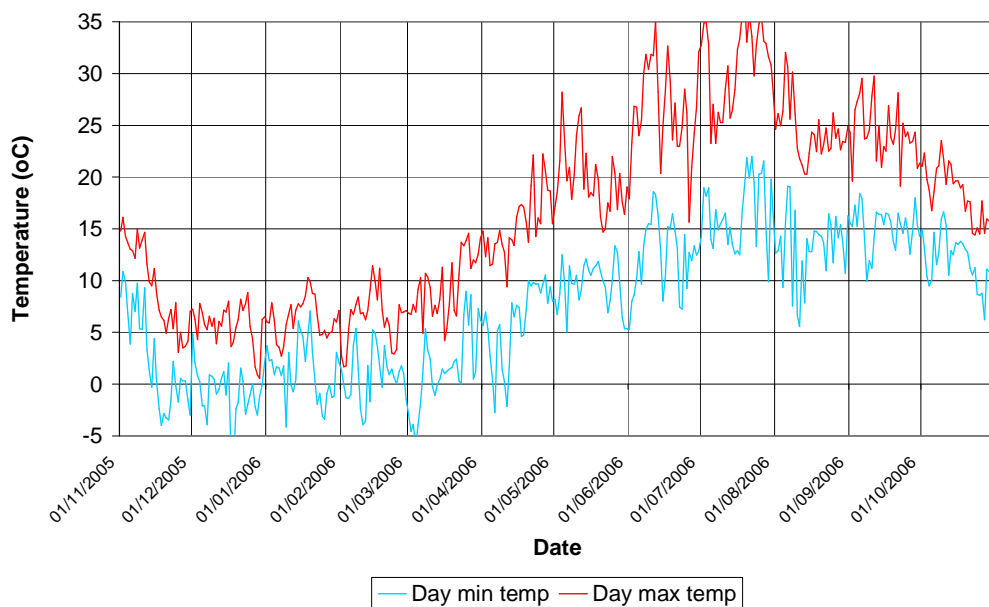


Figure 6 Daily maximum and minimum temperatures during third year in PTF building

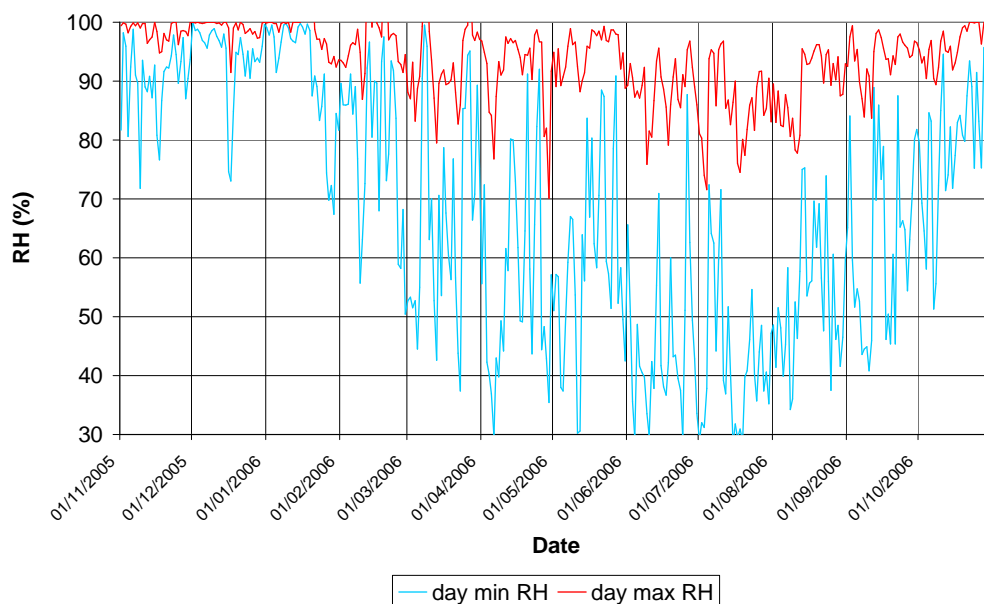


Figure 7 Daily maximum and minimum relative humidity during third year in PTF building

6.1.2 Potential monitoring

Figure 8 shows the half cell potential readings on the stressed tendon T1 Inside before and after introduction of liquid into the voids, and after about one year, two years and three years – prior to the final destructive examination. The potentials had changed relatively little over the third year relative to values at the end of the second year. Potentials were less negative in the ‘Low Cover’ segment; here the tendon was not directly in contact with the chloride solution introduced into the void.

Figure 9 shows the potential readings on the unstressed laboratory specimens. After three years exposure all specimens had potentials indicative of active corrosion. In specimen C (where there was a void between two grouted sections with chloride in the grout) the potential was less negative in the void; this probably resulted from the void being filled with tap water rather than chloride solution.

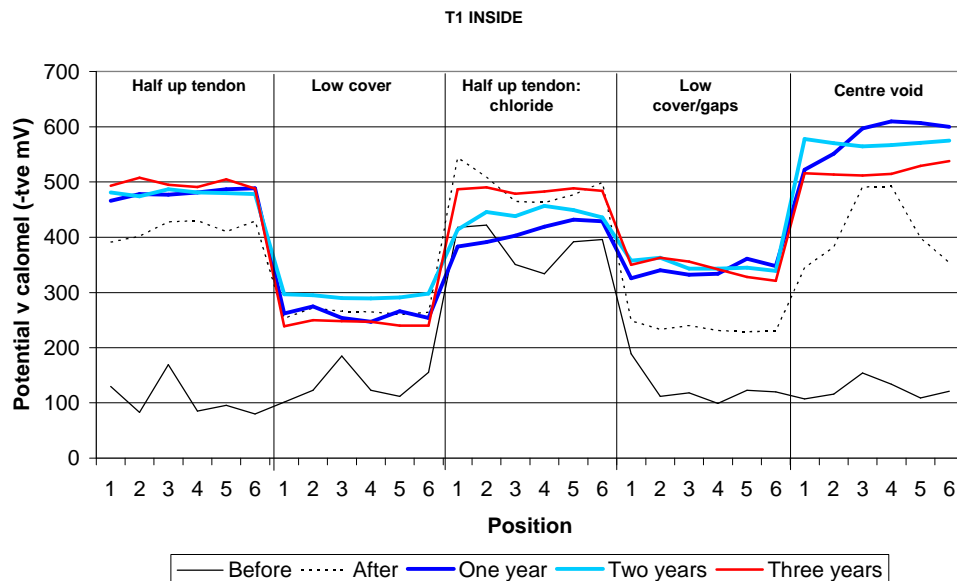


Figure 8 Potential measurements before and after introduction of liquid into voids, and after one year, two years and three years: side T1 In

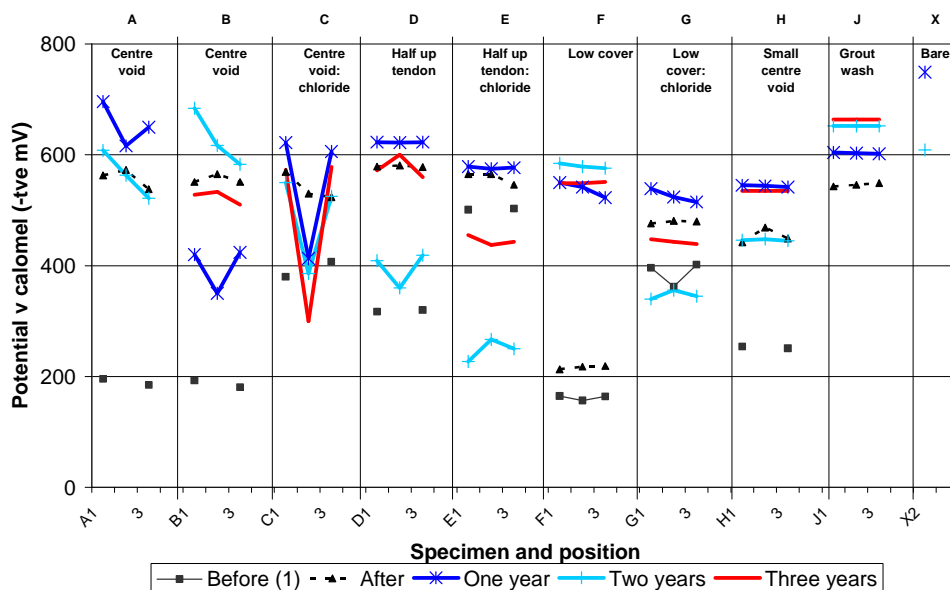


Figure 9 Potential measurements before and after introduction of liquid into voids, and after one year, two years and three years: unstressed specimens

6.2 Destructive examination after three years exposure

6.2.1 *Appearance of stressed tendons*

The tendon removed from the centre void segment was heavily corroded in the void zone. Loosely adherent corrosion products were relatively easily removed by wire brushing to reveal significant loss in section on all the exterior wires (Figure 10); there was little corrosion on the tendon away from the void zone. When the individual wires comprising the tendon were separated some corrosion could also be seen on the central straight wire. After derusting the loss in section on the exterior wires could be clearly seen; it was estimated that loss in cross-sectional area was around 20%. Corrosion on the central wire was limited to relatively minor pitting.

The tendon from the segment where chloride-free grout had been cast half way up the tendon was corroded along its length (Figure 11) with corrosion concentrated on the sides of the tendon (ie at the interface between the tendon and the grout). Wire brushing revealed a rough striated surface with some pitting and loss in section. After derusting one position of significant loss in section could be seen although this was much less severe than on the centre void wires. There was also some pitting on the central wire

The tendon from the segment where grout containing chloride had been cast half way up the tendon was also corroded along its length (Figure 12) with corrosion concentrated on the side of the tendon that had been in contact with the grout. The condition of the individual wires was similar to the tendon with chloride free grout.

The tendon from the segment with low cover and gaps down to the steel was most corroded in the gap locations (Figure 13) but corrosion had spread beyond the gap zone. Corrosion in the gap zones was most severe on the upper side (ie the side in contact with chloride solution) but corrosion was evident in other areas as well. There were some areas of loss in section on the exterior wires but this was not as severe as in the central void specimens. There was also some pitting on the central bar.

The tendon from the segment with low cover along the whole length of the tendon was the least corroded with only patches of relatively light surface rusting (Figure 14). After derusting some relatively light pitting could be seen on both the exterior and central wires and, in this case the central wire was similar to the exterior wires.

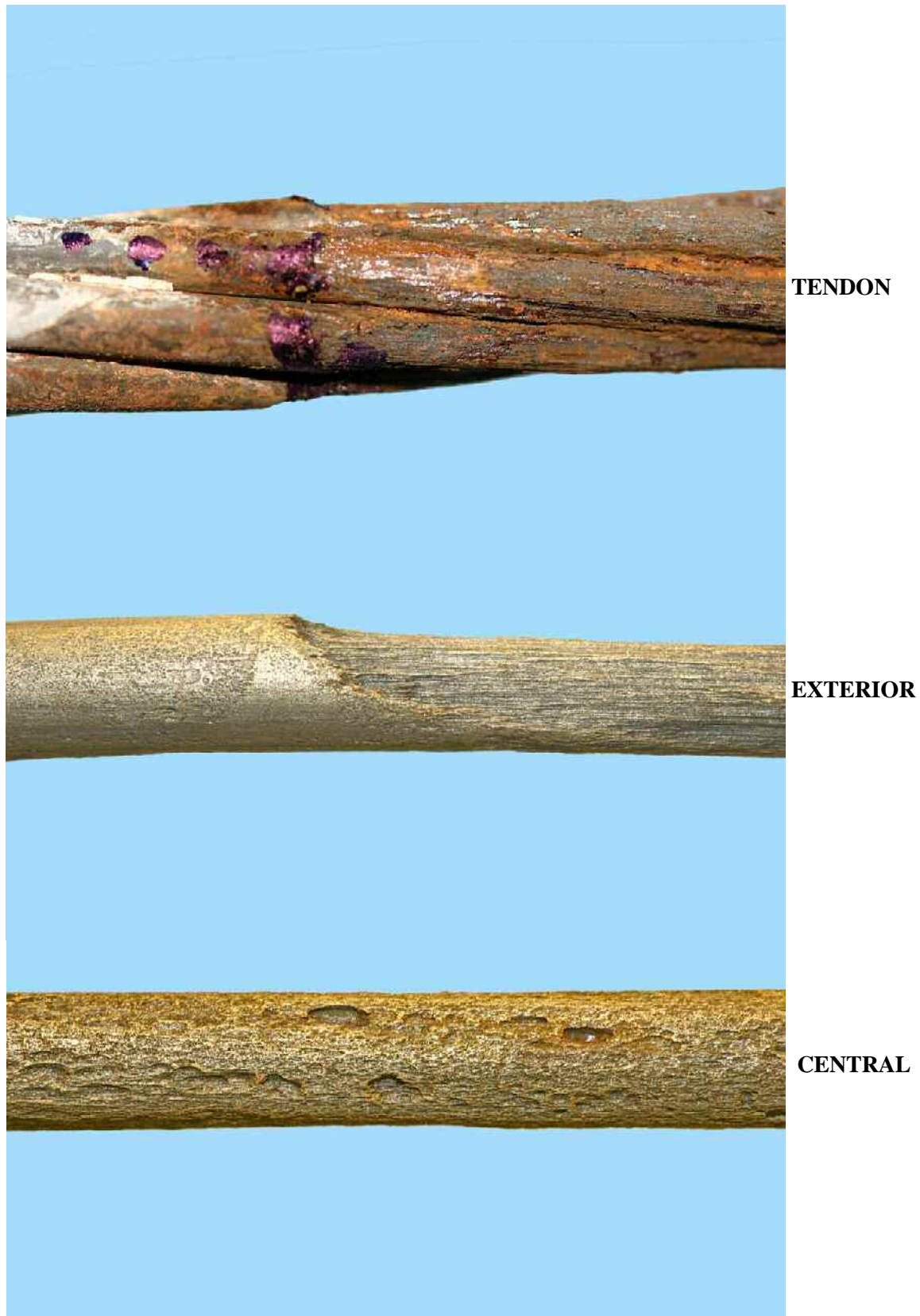
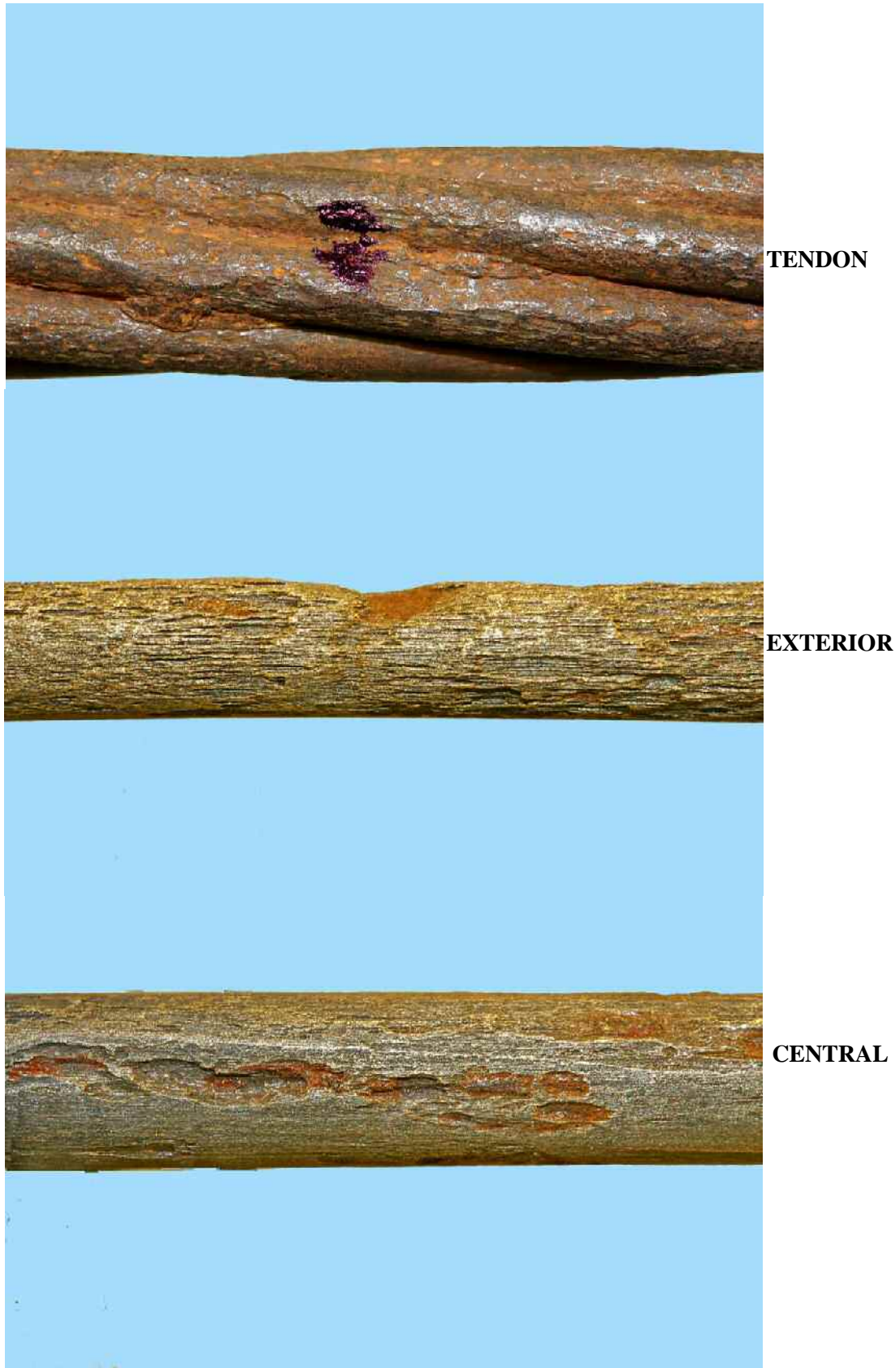
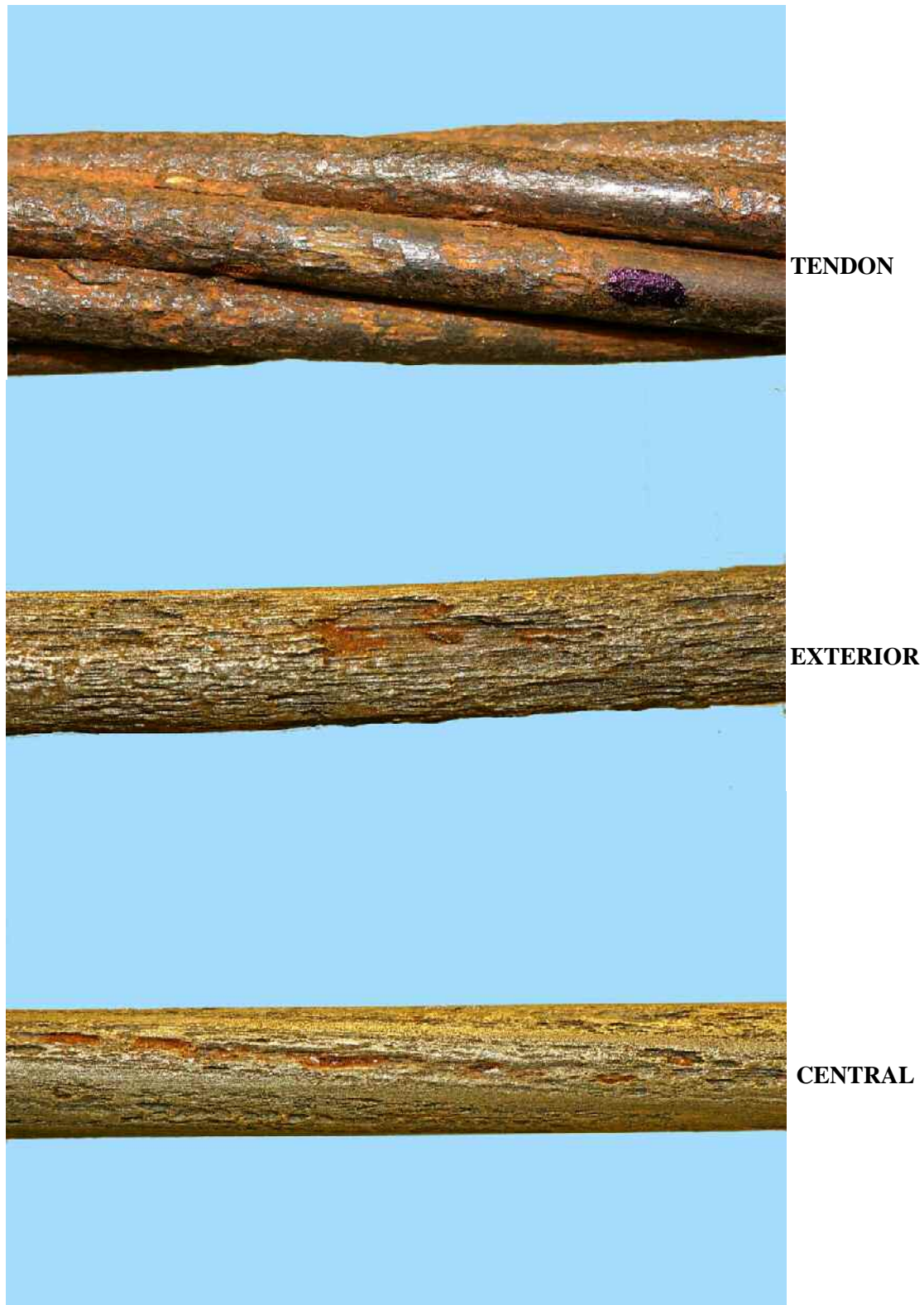


Figure 10 Appearance of rusted tendon and individual wires after three years exposure: Centre void



**Figure 11 Appearance of rusted tendon and individual wires after three years exposure:
Grouted half way up tendon**



**Figure 12 Appearance of rusted tendon and individual wires after three years exposure:
Grouted half way up tendon with chloride in grout**

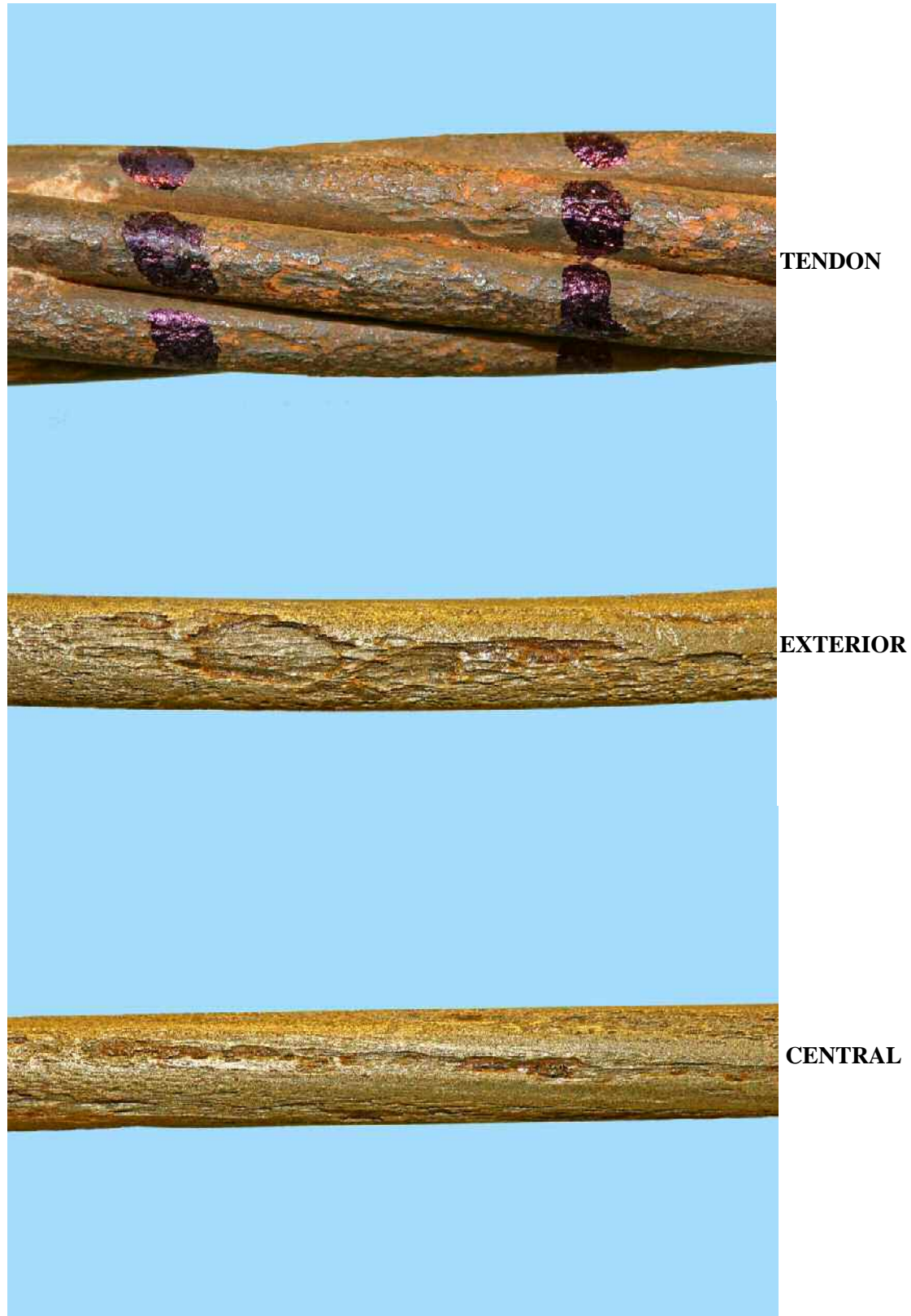


Figure 13 Appearance of rusted tendon and individual wires after three years exposure: Low cover with gaps

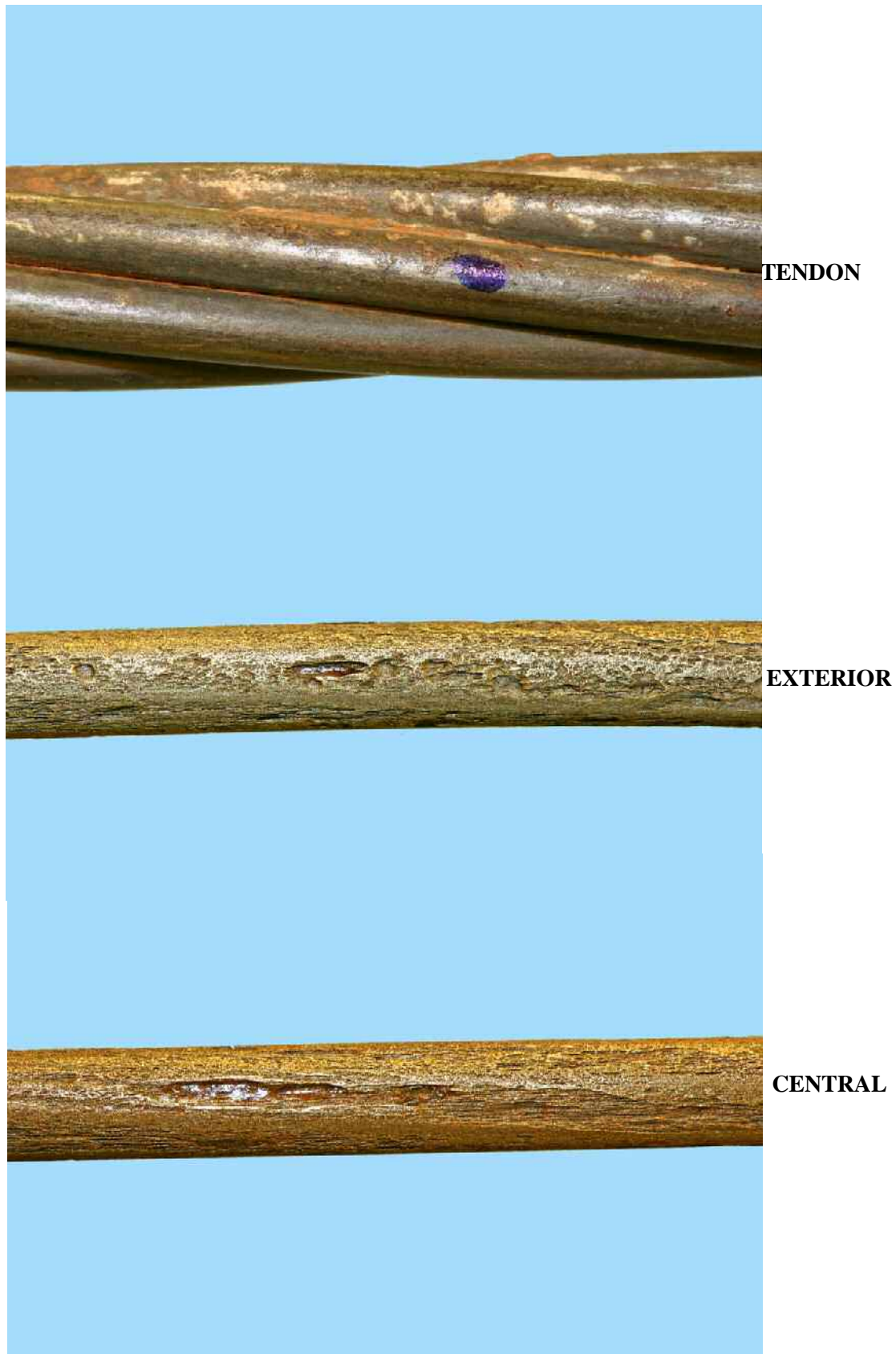


Figure 14 Appearance of rusted tendon and individual wires after three years exposure: Low cover

6.2.2 *Appearance of unstressed tendons*

The unstressed centre void tendon (Specimen B) was similar in appearance to the stressed equivalent. There was little corrosion away from the void but there was considerable loss in section within the void. There was also some roughening of the surface and pitting on the central wire. (Figure 15).

The unstressed centre void tendon (Specimen C), where chloride had been cast into the grout, was corroded mainly in the void area but the corrosion was much less severe than in specimen B. (Figure 16). There was also some corrosion away from the void area.

The wires in the unstressed tendon with grout half way up the tendon (Specimen D) had a generally rough surface with some pitting corrosion superimposed in some areas; there was also extensive corrosion product between the wires. There was some minor loss in section on some of the exterior wires and some pitting. The central wire had a roughened surface with some pitting.

The wires in the unstressed tendon with grout containing chloride cast half way up the tendon (Specimen E) had a roughened surface with some minor loss in section. This was worst in positions in the grout. The central wire was roughened with some minor pitting.

The wires in the unstressed tendon with low cover (Specimen F) had a rough surface with some significant localised loss in section on the exterior wires (Figure 17); there was also some pitting on the central wire but no significant loss in section. The grout in this specimen had cracked above the tendon. This would have allowed increased access of chloride solution to the tendon exacerbating the corrosion.

The grout in the unstressed tendon with low cover and chloride in the grout (Specimen G) had also cracked above the tendon. However whilst the wires in this specimen had roughened surfaces with some pitting on both the exterior and central wires, there was no significant loss in section.

The wires in the tendon with a small centre gap (Specimen H) were corroded both at and away from the gap area. However the grout had cracked above the tendon thereby allowing increased access of chloride solution to the whole length of the tendon. Wires were roughened with some pitting but there was no significant loss in section.

The wires from the grout washed tendon (Specimen J) had roughened surface with some pitting but no significant loss in section.

The bare tendon (Specimen X) appeared to be heavily corroded but the corrosion products were all non adherent and were easily removed. There was some roughening of the surface of the wire with minor pitting but no significant loss in section.

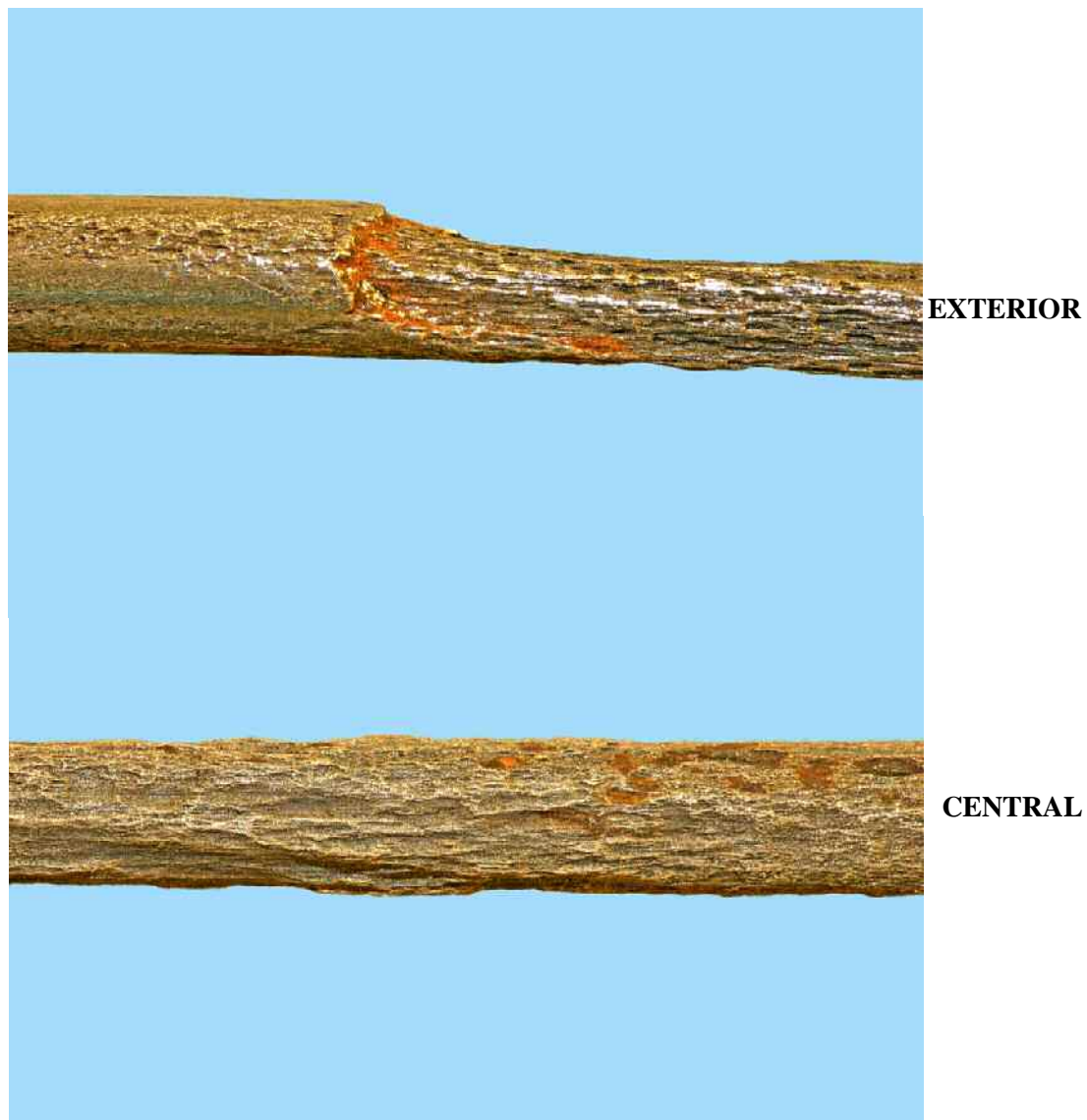


Figure 15 Appearance of individual wires from unstressed specimens after three years exposure: Centre void

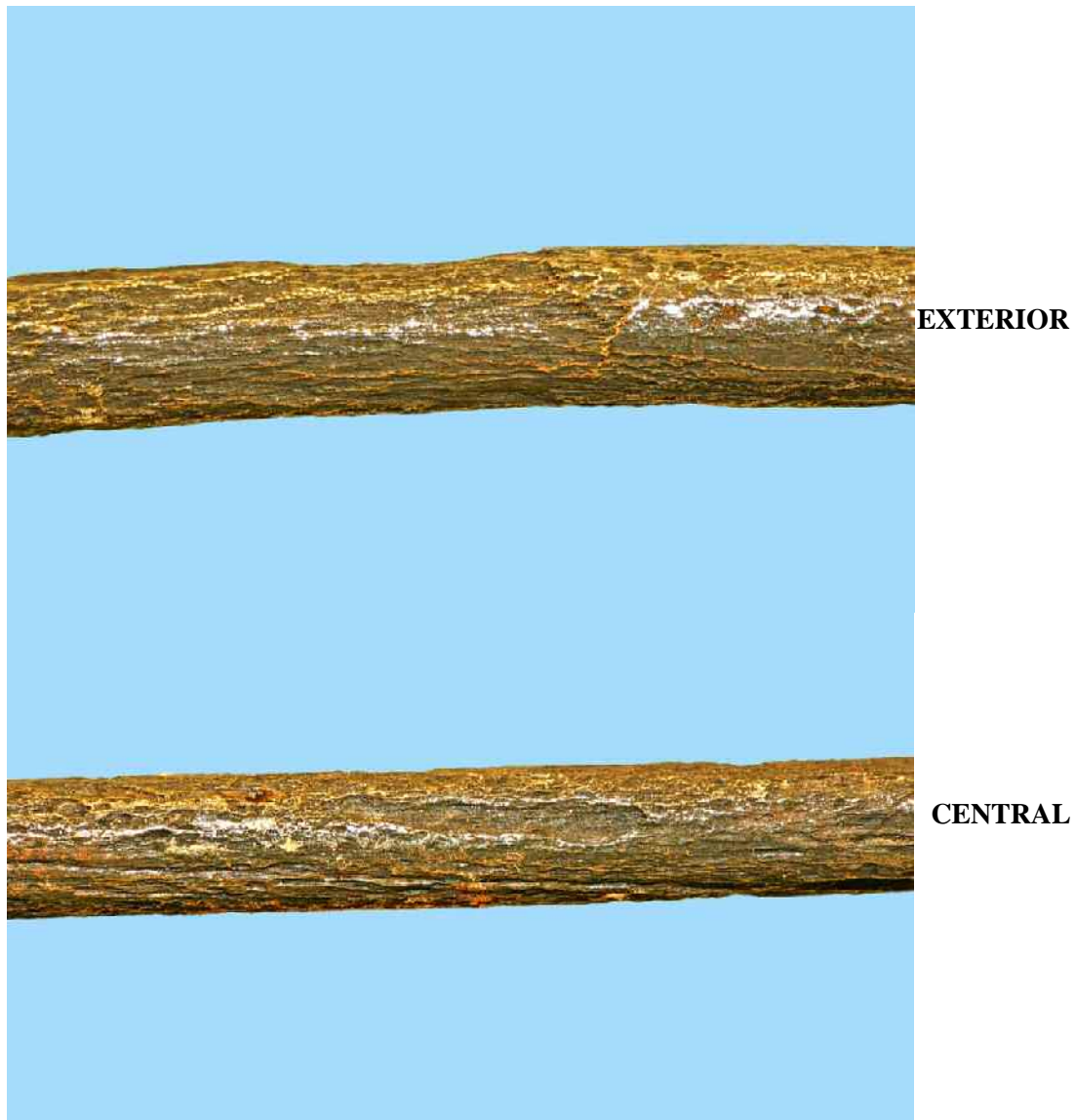


Figure 16 Appearance of individual wires from unstressed specimens after three years exposure: Centre void with chloride in grout

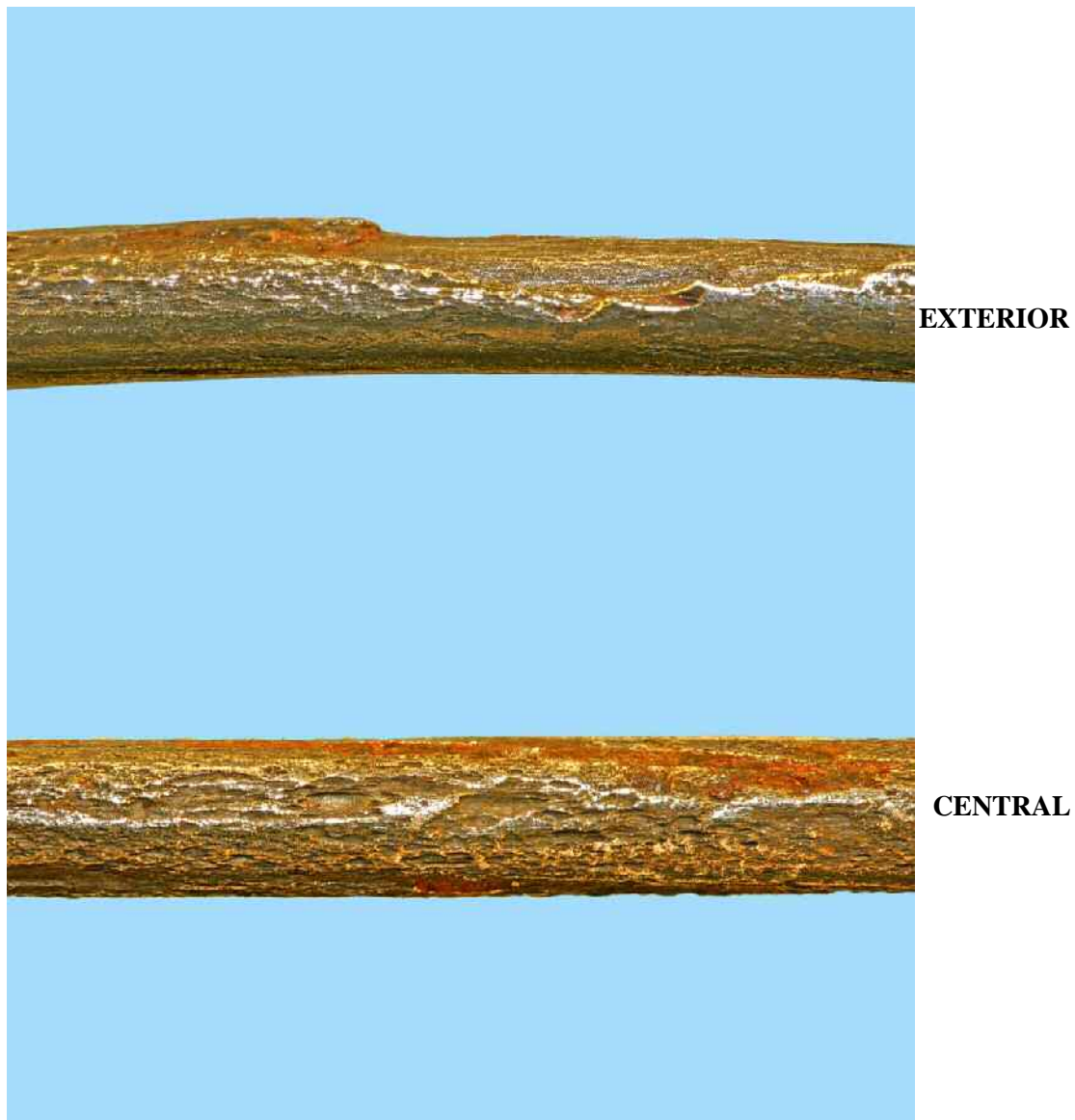


Figure 17 Appearance of individual wires from unstressed specimens after three years exposure: Low cover

7 Discussion

In the previous destructive examination of a stressed tendon (after two years exposure) the most severe corrosion was found in the segment with a bare section between two grouted sections. At that time only one wire had been affected with a maximum section loss of only 10%. After three years, loss in section in that position had increased dramatically so that all exterior wires had corroded with a loss in section of about 20% on each. It is likely that the tendon in the grouted section was providing a cathodic region which increased the corrosion in the void. The conditions in the void were quite severe and specific to this particular experiment involving varying states of immersion of the tendon in chloride solution so this could represent a relatively high rate. It would be useful to carry out further testing of this type of void under a range of immersion conditions.

Significant corrosion was also developing in other positions where the tendon was directly exposed to chloride solution but was not so extreme. It was also apparent that even a low cover of grout over the tendon does provide significant protection.

Corrosion was found within the body of the tendon on the straight central wire indicating that chloride solution could penetrate to that level; any modelling of deterioration rates would need to take this into account. The severity of corrosion was generally less in this position so a visual inspection of the exterior of a tendon would be looking at the most important position. However visual inspection has limitations in that, without removing the corrosion products, loss in section may not be apparent.

The unstressed specimens gave similar types of corrosion to those found on the stressed specimen. It is not possible to compare the severity of corrosion directly as the exposure conditions were not identical. However the results do support the use of unstressed specimens, which are much easier to deal with, in examining the potential effects of other exposure conditions.

8 Conclusions

An experiment was carried out to examine the influence of voids in post tensioning ducts on the corrosion rate of the tendons. The most severe corrosion was found in a chloride filled void where a section of bare tendon lay between two grouted sections. This had resulted in about 20% loss in section on all exterior wires after three years exposure.

Corrosion was active within the body of the tendon as well as on the exterior surface but was less severe. This would have to be taken into account in any modelling of deterioration rates.

Corrosion on equivalent unstressed specimens was similar in type to that found on the stressed specimens. This supports the use of unstressed specimens, which are easier to deal with, in examining the potential effects of other exposure conditions.

9 Acknowledgements

The work described in this report was carried out in the Infrastructure and Environment Division of TRL Limited. The author is grateful to Atef Badr for assistance with the examination of the tendons and Dr R Woodward who carried out the quality review auditing of this report.

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