DURABILITY OF CONCRETE PIPES IN CHLORIDE ENVIRONMENT

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Reinforcement corrosion is a key factor to accurately predict the service-life of concrete structures in chloride environments. In this study, eight concrete cores extracted from 49 and 55 years old in-service pipes with exposure to chlorides in a tidal exposure condition were investigated. Total chloride contents at the steel-concrete interface, corrosion rates of the steel bars and crystalline phases of corrosion products were evaluated. The results indicate that the total chloride content at the steel-concrete interface were significantly higher than the critical chloride thresholds suggested by ACI and RILEM. However, as most of the steel bars showed very low or no corrosion where corroded surfaces observed were always facing the inside of the pipes. No correlation between total chloride contents and corrosion rates could be observed. Only the steel bars extracted from core CB4 were almost totally corroded because of an excessively low concrete cover of 10 mm on the interior of a pipe invert. The low corrosion rate of the other steel bars can be attributed to the delay in oxygen diffusion and oxygen availability at the steel-concrete interface. Based on the experimental results collected, conservatively, a concrete cover of 25 mm is suitable to ensure 100 years service-life without any reduction in structural capacity or corrosion induced concrete cracking, increasing the concrete cover further being unnecessary.

1. INTRODUCTION

Reinforcement corrosion is one of the most important durability issues in concrete structures. The steel bars in concrete are initially surrounded by a passive film with pH value of 12.5 or higher created by the high alkalinity of the pore solution [1, 2]. The high pH value of the concrete pore solution naturally prevents steel reinforcement corrosion, so-called passivation stage. Active corrosion starts when external aggressive agents reach the reinforcement and alter the passive film. There are two stages in the reinforcement corrosion process including initiation stage and propagation stage, as suggested by Tuutti [3]. The initiation stage describes the diffusion of aggressive ions toward the steel-concrete interface, predominantly chloride ions in marine environments. When chloride concentration reaches the chloride threshold at the steel-concrete interface, the corrosion propagation stage starts. In the propagation stage, corrosion products (rust) form and accumulate along the steel-concrete interface. The corrosion products are a mixtures of iron oxides. Their volume can be from twice to four times larger than that of iron [4, 5], leading to concrete cracking and spalling as well as a loss of bearing capacity due to the resulting steel bars cross-section reduction [5-7].

Traditional design approach adopted for bridges and buildings relies on the implicit assumption that no active corrosion should occur during the service life of the structure [8]. As a result, only the initiation phase of the corrosion process is considered. The service life is defined by the time required for chloride to reach the chloride threshold at the steel depth in the concrete. For bridge and building structures, it is assumed that corrosion damage (concrete cracking) will occur relatively quickly as soon as corrosion propagation starts which is the main justification of this service life design approach. However, field observations seem to show that this assumption is not appropriate for concrete pipes. Despite high chloride levels, corrosion of reinforcement is only marginal after a very long time without leading to any concrete cracking. The lack of oxygen is suspected to be the governing factor of steel corrosion limitation suggesting that the propagation phase of steel corrosion should be considered as part of the service life of concrete pipes. The key issue is the risk that overly conservative specifiers may influence Standards and specifications such that unnecessary and costly durability requirements, such as excessive cover to steel, are prescribed when concrete pipes are exposed to chloride environments.

In this study, eight concrete core specimens including steel bars extracted from several in-service pipelines in Mackay, Queensland, Australia were investigated. All pipelines were exposed to chloride environment from both inside surface (chloride ions from tidal seawater) and outside surface (chloride ions from coastal ground). Pipes have been in service and continuously in contact with chloride ions for 49 years and 55 years. Chloride content at the steel-concrete interfaces and the gravimetric mass loss of the steel bars were determined. Additionally, the corrosion products on the steel bars were collected and analysed by X-ray diffraction (XRD). The role of oxygen availability and total chloride content at the steel-concrete interface on corrosion process and concrete pipes service life are discussed in relation with the concrete cover to reinforcement.

2. SPECIMENS AND METHODOLOGY

2.1 CONCRETE PIPES AND CORING LOCATIONS

The concrete cores were extracted from pipelines located at Mackay City, Queensland, Australia. Mackay City is classified as tropical weather in Australian Standard AS3600 [10] with average temperature ranging from 19.2°C to 26.6°C and average annual rainfall of 1594 mm [11]. As presented in Fig. 1, the first location is on Chain Street and second location is on East Gordon Street. Time in service of these pipes is 49 years and 55 years respectively. The concrete pipes in both locations have been directly exposed to tidal sea water through Sandfly Creek.

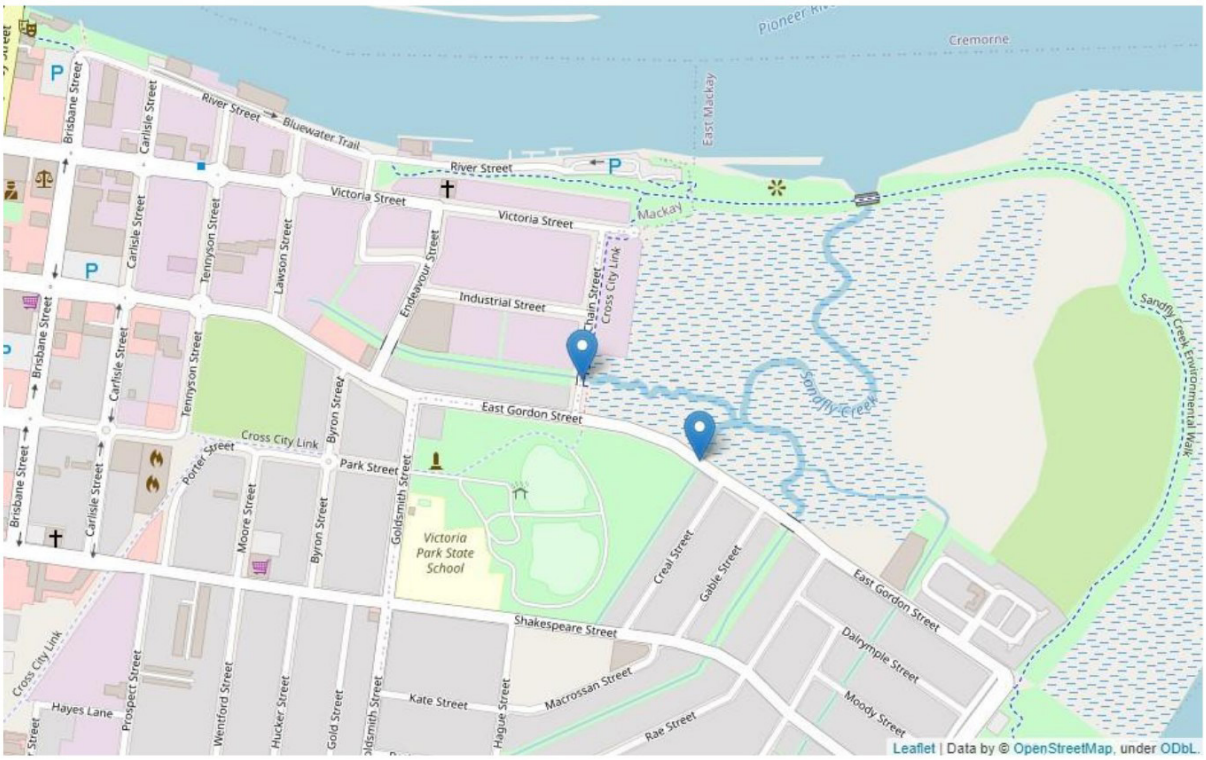

FIGURE 1. Concrete pipes locations

All pipelines diameter is 1500 mm. Pipelines at Chain Street denoted as C is a group of six cell pipelines (Fig. 2) while only one pipeline was investigated at Gordon Street, denoted as G.

FIGURE 2. Concrete pipes at Chain Street

Cores were sampled at two different locations along the perimeter of the pipe cross-section (Fig. 3a). The concrete cover is not constant depending on the location along the perimeter. For cores sampled on the side (type S), the lowest concrete cover is facing the external pipe surface. For cores sampled at the bottom (type B), the lowest concrete cover is facing the internal pipe surface. Both of these coring locations are in the intertidal zone. The concrete cores had 100mm diameter and varying height depending on the thickness of pipelines. All cores contained at least one steel bar allowing to evaluate the corrosion rate of reinforcement. An example of concrete cores is shown in Fig 3b. In total, 8 cores were investigated in this study and the details of each core are presented in Table 1.

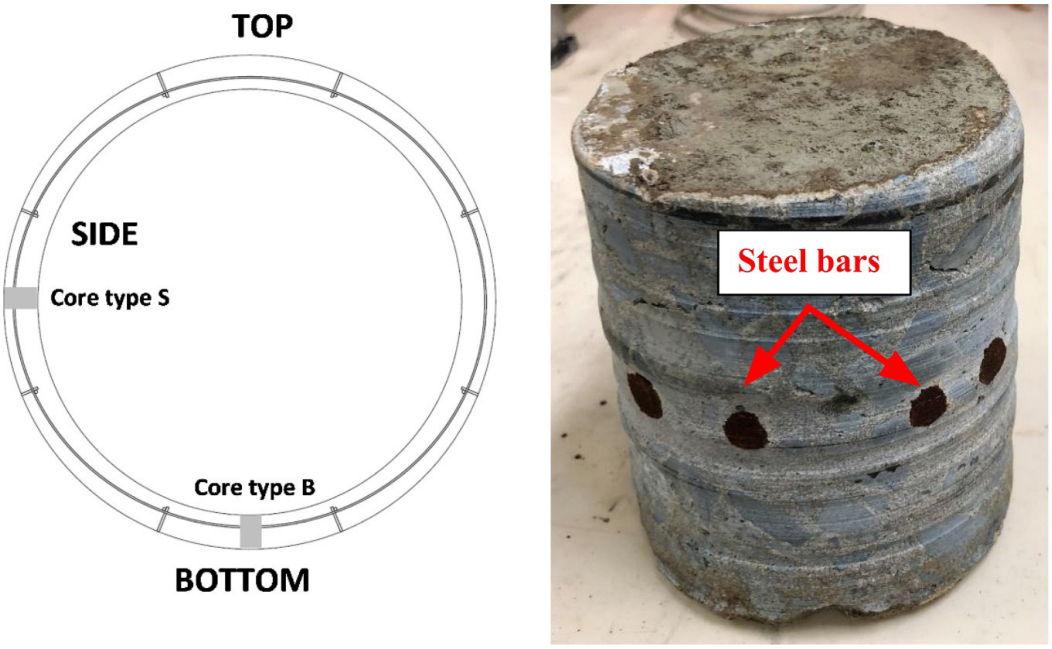

FIGURE 3. a) Typical cross-section of pipelines and coring locations. b) Concrete core

As shown in Table 1, cores were also sampled at different distances from the pipe's outlet, varying from 2 m to 11 m.

Name	Pipe location	Core location in pipeline	Distance from the outlet (m)
CS2	Chain Street	Side	2
CB2	Chain Street	Bottom	2
CS4	Chain Street	Side	4
CB4	Chain Street	Bottom	4
GB2	Gordon Street	Bottom	2
GS3	Gordon Street	Side	3
GB10	Gordon Street	Bottom	10
GS11	Gordon Street	Side	11

TABLE 1. Details of concrete cores in this study.

2.2 METHODOLOGY

Concrete powders were sampled every 1 mm depth until reaching the steel-concrete interface (from both inside and outside surfaces of the pipes) by using a Germann Profile Grinder. The total chloride content in the concrete powders was then measured by potentiometric titration following ASTM C1152 protocol [12].

Steel bars were extracted from the concrete cores and a metallic brush was used to remove the remaining cement paste residue from the steel bars surface. Subsequently, the gravimetric loss of mass of the steel bars was measured based on ASTM G1 using a combination of reagent grade hydrochloric acid, antimony trioxide and stannous chloride [13]. The measurement was repeated several times until the mass loss started to plateau.

The corrosion products (i.e, rust) were collected from heavily corroded reinforcement surface prior to the mass loss measurement. They were crushed into powder using a ball mill. X-ray diffraction (XRD) pattern of corrosion products was obtained by using X-ray

diffractometer Phillips X'Pert Pro Multi-purpose (MPD). The XRD analysis configurations included Cu-Kα radiation with 0.15418 nm wavelength at 45 kV and 40 mA, 0.013° 2θ step size and a sample spinner. XRD phase identification was carried out by using the HighScore Plus software.

3. RESULTS AND DISCUSSION

3.1 TOTAL CHLORIDE CONTENT AT STEEL-CONCRETE INTERFACE

Fig. 4 presents the total chloride content at steel-concrete interface including interface facing inside (chloride from the seawater) and outside (chloride from the ground) against corresponding inside or outside concrete covers. As the concrete mix design was unknown, the total chloride contents showed as % of binder was calculated with the assumption of 400 kg/m3 OPC in a 50MPa concrete mix.

From Fig. 4, the highest and smallest chloride content at the steel-concrete interface were 6.06% and 0.89% respectively. All chloride contents are significantly higher than the chloride threshold of 0.2% and 0.4% for steel bars depassivation recommended by ACI and RILEM respectively [14, 15]. In addition, no correlation could be observed between concrete cover and chloride content at this stage of service-life. All steel bars were in contact with concrete with a very high total chloride content regardless the concrete cover ranging from 10 mm to 60 mm.

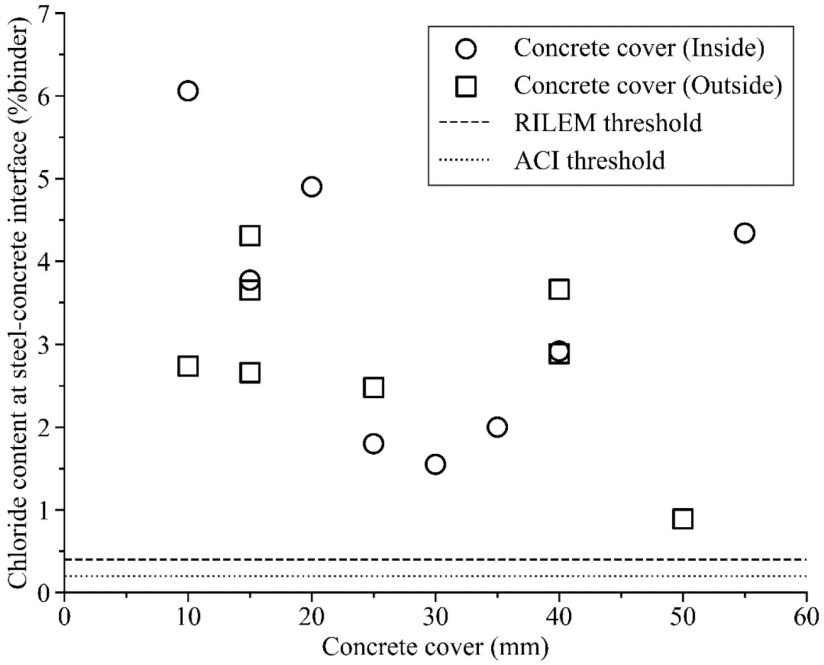

FIGURE 4. Chloride content at steel-concrete interfaces facing inside and outside the pipes and critical chloride thresholds according to ACI and RILEM.

Despite the high chloride contents measured at the steel-concrete interface, corrosion products were not observed on all steel bars. Fig. 5a shows an example of steel bar extracted from core specimens CS2 with chloride content ranging from 1.80 to 2.48 % of cement exhibiting no corrosion product. Overall, no correlation was observed between chloride content and corrosion rate of reinforcement. In addition, Fig. 5b and Fig. 5bc show a steel bar extracted from core GB10 displaying corrosion only on the steel surface facing the internal pipe surface side. More discussion is provided in the following section.

FIGURE 5. (a) Steel bar extracted from core CS2 displaying no corrosion; (b and c) Steel bar extracted from core GB10 displaying corrosion only on the internal pipe surface side.

3.2 CORROSION RATE EVALUATION BY STEEL BAR GRAVIMETRIC MASS LOSS

Corroded surfaces observed on the extracted steel bars were always facing inside the pipes. Hence, it is assumed that steel corrosion was predominantly the result of both chloride and oxygen diffusion from the aerated interior surface of the pipes. Fig.6 shows the corrosion rate of all steel bars extracted from the concrete cores against the concrete cover facing inside of the concrete pipes. The corrosion rate was calculated as the percentage of gravimetric mass loss determined by using ASTM G1 method [13] over the mass of uncorroded steel bars.

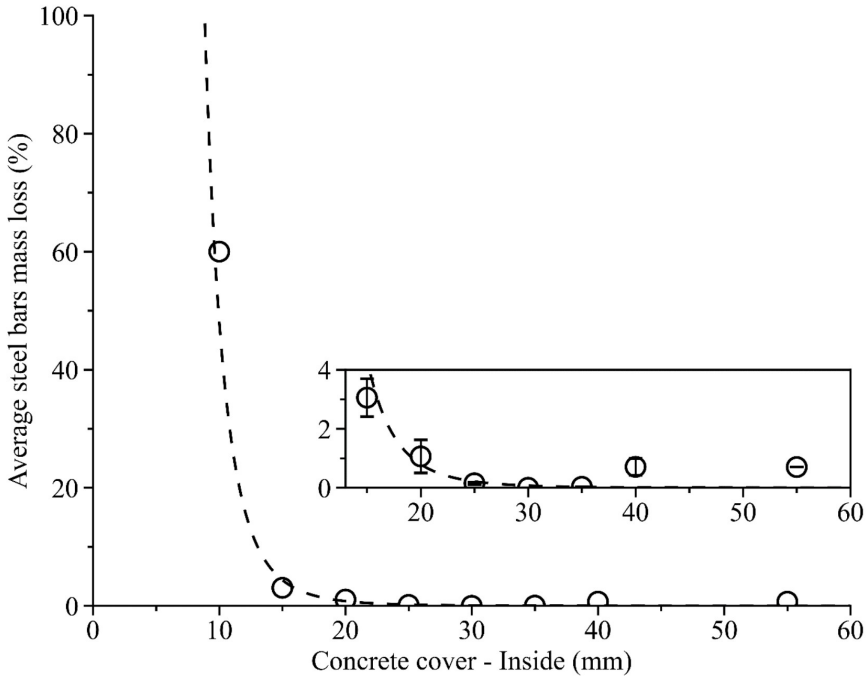

FIGURE 6. Corrosion rate of steel bars versus concrete cover facing inside the pipes

The steel bars of core CB4 were heavily corroded and less than half of the steel bar could be recovered. Consequently, the authors assumed that the corrosion rate of steel bars from CB4 specimen was 60% as presented in Fig. 6. Except for CB4 specimen, the corrosion rate of all other steel bars was extremely low, less than 4% or no corrosion at all. For those bars, the low corrosion rate combined with high chloride content indicated that corrosion propagation stage has been ongoing for a long time but at a very slow rate. Apart from the chloride threshold, reinforcement corrosion process also depends on oxygen availability at the steel-concrete interface, so-called oxygen diffusion rate-determining factor [16]. The environmental conditions of the pipelines including seawater and ground submersion as well as high humidity inside the pipelines are suspected to greatly delay oxygen diffusion and its availability at the steel-concrete interface. Indeed, the pores of the concrete at the interior of the pipes are saturated most of the time. Oxygen diffusion, depending on the concrete cover, can require long drying phases to allow oxygen renewal at the steel-concrete interface. According to Figure 6, 20 mm concrete cover seems to be suitable to stop the oxygen renewal at the steel-concrete interface. However, 10 mm concrete cover can lead to severe steel corrosion as demonstrated by core CB4 results.

Traditional service life prediction models usually assume that the end of service life occurs when the total chloride content at steel-interface is reaching the chloride threshold. However, from Fig.6 results as an indicator of the real performance of pipelines under natural severe environments, the propagation phase of reinforcement corrosion should be accounted as a part of the pipeline service life if the concrete cover is suitable. This is attributed to the absence of heavy reinforcement corrosion in spite of significantly high chloride content exceeding the critical chloride threshold at steel-concrete interface.

For 20 mm concrete cover and considering a grade 40 MPa concrete without SCM, it is expected that chloride ions would have reached the reinforcement leading to corrosion after about 20 to 25 years depending on the chloride diffusion modelling assumptions (chloride threshold, chloride surface concentration… etc). As a result, the steel reinforcement of both Chain and Gordon Street pipes has been corroding for at least 25 years when the cores were sampled. The maximum steel mass loss measured for the core with 20mm concrete cover was about 1% (Fig. 6). Assuming a similar corrosion propagation rate over the remaining 50 years of service life, the mass loss of the reinforcement is predicted to reach a maximum of 3% at the end of the pipes service life (100 years). The loss of mass required for concrete cover cracking can be calculated using Vidal et al model [17]. For a steel bar diameter of 6.5mm, a concrete cover of 20 mm and a pitting corrosion factor α of 4, the minimum loss of mass required for concrete cracking can be estimated equal to 4.4%. Therefore, conservatively, a concrete cover of 25 mm is suitable to ensure 100 years service-life without any reduction in structural capacity or corrosion induced concrete cracking, increasing the concrete cover further being unnecessary.

3.3 XRD OF CORROSION PRODUCTS (RUST)

Corrosion products were collected from heavily corroded steel bars from core CB4. It has not been possible to extract corrosion products from other steel bars for XRD analysis due to the very low corrosion rates. The XRD pattern of the corrosion products is presented in Fig. 7. The presence of Quartz is due to the concrete aggregates. The corrosion products were a mixture of different iron oxides including Magnetite/Maghemite, Akaganeite and Goethite. Magnetite and Maghemite, which cannot be separated in XRD analysis, are the main crystalline corrosion products with the highest peak at around 35.45 °2θ. This significant presence of ferrous containing minerals like magnetite and maghemite indicate corrosion occurred with limited dissolved oxygen. The presence of Akaganeite in the XRD pattern can confirm the involvement of chloride ion in the formation process of corrosion products [18].

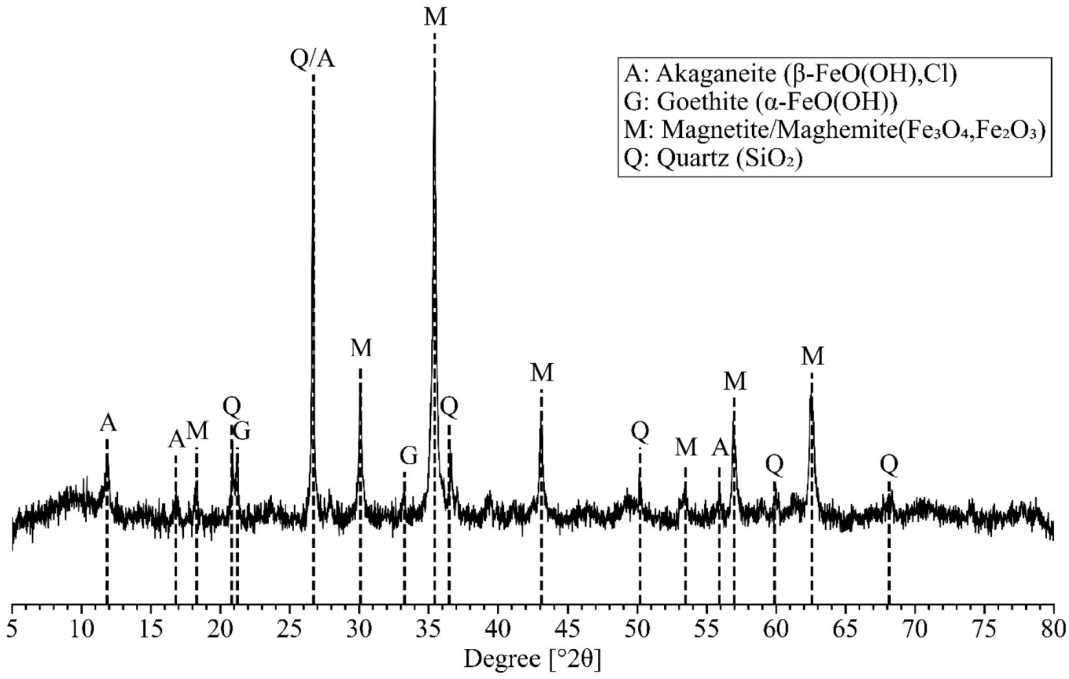

FIGURE 7. XRD pattern of corrosion products (rust)

4. CONCLUSION

This study investigated the chloride-induced reinforcement corrosion of concrete core specimens extracted from tidal exposed 49 and 55 years old in-service concrete pipes. Chloride contents at the steel-concrete interface, corrosion rates of the steel bars and XRD pattern of corrosion products were measured. The main outcomes of this study are summarised as follows:

- The chloride contents at the steel-concrete interface facing inside and outside the pipes were significantly higher than the chloride threshold recommended by ACI and RILEM. The highest and smallest chloride content at the steel-concrete interface were 6.06% and 0.89% of cement respectively. However, most of the steel bars showed very low corrosion on the internal side or no corrosion, leading to no correlation between total chloride contents and corrosion rates.
- The corrosion results indicated that all steel bars presented extremely low corrosion rates, less than 5% or no corrosion at all, except for the steel bars in core CB4 which were almost totally corroded because of an excessively low concrete cover of 10 mm. The low corrosion rate of the other steel bars can be attributed to the delay in oxygen diffusion and oxygen availability at the steel-concrete interface.
- The high level of humidity in the pipe concrete is suspected to greatly delay oxygen diffusion. Oxygen diffusion, depending on the concrete cover, can require relatively long drying phases to allow oxygen renewal at the steel-concrete interface.
- The corrosion products identified in this study are consistent with results of previous studies investigating reinforcement corrosion in natural chloride environments, including Magnetite/Maghemite, Akaganeite and Goethite.
- Based on the experimental results collected, conservatively, a concrete cover of 25 mm is suitable to ensure 100 years service-life without any reduction in structural capacity or corrosion induced concrete cracking, increasing the concrete cover further being unnecessary.

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