

Corrosion propagation of prestressing steel strands in concrete subject to chloride attack

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ABSTRACT

A review of research literature suggests that steel corrosion in concrete can accelerate if the corroding steel is under high levels of stress but this important phenomenon has not been investigated thoroughly. Both laboratory tests and field surveys indicate that the effects of corrosion on structural behaviour in reinforced and prestressed concrete structures are different, with the latter having less concrete cracking but more serious structural collapses. The intention of this paper is to investigate the corrosion propagation of prestressing steel strands in chloride-laden environment. A long term experimental program is presented in which the corrosion of twelve prestressing steel strands embedded in concrete was examined. The effects of the level of stresses in the steel and type of steels on corrosion rate are studied. It is found that the corrosion rate of prestressing steel strands in concrete increases with the increase of the level of stresses applied and that the pitting corrosion is the main form of prestressing steel corrosion in chloride-laden environment. The paper concludes that the corrosion of prestressing steel in concrete structures poses higher risk to the structure than that of reinforcing steel in terms of structural collapse.

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1. Introduction

Steel corrosion in concrete has long been recognized as a global problem that has caused widespread damages to concrete structures, ranging from concrete cracking, spalling to ultimate structural collapse [1]. It is estimated that corrosion related maintenance and repairs for concrete infrastructure cost around \$100 billion per annum in the world [2]. Evidently, to ensure the safe and economic operation of corrosion prone concrete structures during their whole service life it is of paramount importance to determine how corrosion propagates and its resultant structural deterioration so that the risk of structural failures and cost to maintain structural services can be optimized in the management of corrosion affected concrete structures.

Research on steel corrosion in concrete has been both intensive and extensive in the past few decades [3–11]. A review of literature (see references) shows, however, that research on steel corrosion in concrete is more focused on reinforced concrete (RC) structures than on prestressed concrete (PC) structures. Whilst the underlying principles of corrosion science, e.g., electrochemical process, are the same for both reinforcing steel and prestressing steel, the differences in mechanical and physical conditions of the steels used in these two types of structures, in particular the high level of

stresses in prestressing steels (strands), their microstructure, their smooth surface and small cross-sectional areas, give rise for the need to examine the corrosion propagation separately in PC structures. Research e.g., [12] has shown that, when the corrosion condition at the cathode is sufficient, the reaction rate at the anode will be accelerated due to the high level of stresses in the corroding steel. Furthermore, the effects of corrosion on structural behaviour in these two types of structure are different, with PC structures having less cracking but more serious structural failures, as indicated by more cases of structural collapses of PC structures caused primarily by prestressing steel corrosion. Of many examples [9,13,14], the collapse of Ynysygwas Bridge in Port Talbot, UK (Fig. 1) is the most typical structural collapse caused by corrosion of prestressing steel strands under its own weight without warnings, indicating a considerable reduction of its load carrying capacity due to the reduction of cross-sectional area of corroded prestressing strands [15].

Of many types of corrosion in prestressing steels, the stress corrosion and pitting corrosion have the potential to cause ultimate structural collapse although by different mechanisms [8,9]. Stress corrosion induced structural collapse is initiated by cracking of the prestressing steel whilst the pitting corrosion reduces the cross-sectional area of the prestressing steel and hence the load carrying capacity of the structure. Because of its high level of stresses in steel strands under service conditions, and also due to its brittle nature of stress corrosion cracking (SCC), it is natural that stress

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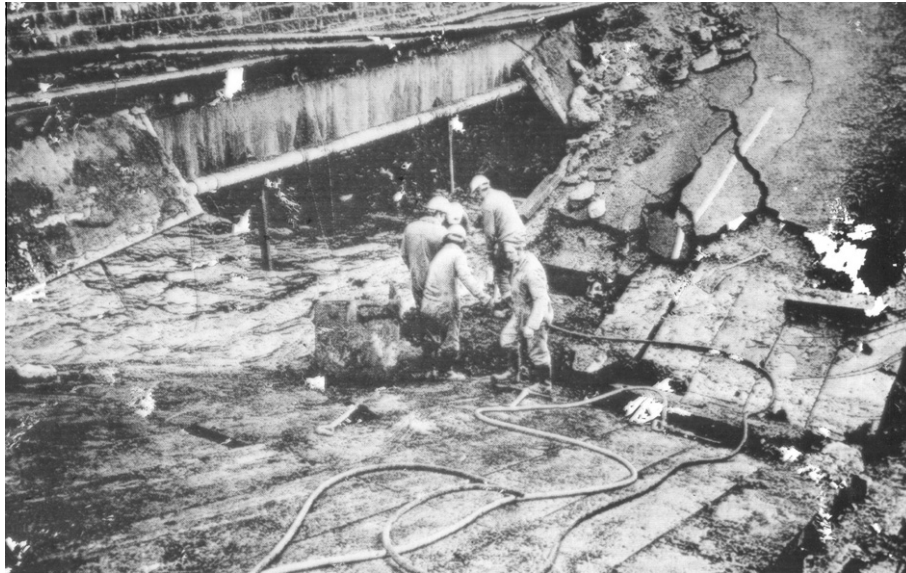


Fig. 1. Collapse of Ynysygwas Bridge in Port Talbot.

corrosion is considered to be more dominant than pitting corrosion in the corrosion process [14,16] even though more research shows otherwise. For example, Klodt [17] and Cherry and Price [18] both studied the corrosion of stress relieved wires submerged in chloride solutions and found that SCC did not occur in chloride environment. More recently, Li et al. [19] carried out long term experiments to investigate the susceptibility of SCC of prestressing steel strands in chloride environment. Both experimental results and theoretical analysis [20] suggest that prestressing steel strands are less susceptible to SCC in chloride induced corrosion.

On the other hand, both experimental results and field experiences (see references above) suggest that a large proportion of structural damages in PC structures, in particular collapses, are caused by pitting corrosion of prestressing steels but insufficient research has been undertaken to study the characteristics of pitting corrosion in PC structures, in particular, corrosion propagation [4,5,21–24]. Previous research [25–27] has shown that, due to their smooth surface from manufacturing process, prestressing strands are protected by a firmer passive film which is more difficult for chloride to penetrate and initiate corrosion. As a result, the corrosion concentrates on a small number of cells, which leads to a distinct pitting corrosion. It is also shown [6,27] that, due to the pitting corrosion, the proportion of brittle fractures of the prestressing strands increases but the ultimate tensile strength and strain of steel strands decrease remarkably as a result of combined stress concentration and reduction in cross-sectional area of steel strands.

Regardless of the failure mechanisms (i.e., SCC or pitting corrosion), a certain degree of corrosion is necessary before the prestressing steel fails, fractured or ruptured. It is in this regard that the present paper investigates the corrosion propagation of prestressing steel strands in chloride environment. In this paper, an experimental program is presented in which the corrosion of twelve prestressing steel strands embedded in concrete was examined in chloride environment. Six ordinary reinforcing steel bars were used as reference under the same test conditions. The effects of the level of stresses in the steel, the type of steel and the level of chloride concentration in concrete on corrosion rate were studied. Also presented in the paper is the theoretical analysis on pitting corrosion, its rate and the effects of the level of stresses and type of steels on corrosion rate.

2. Research significance

Whilst considerable research has been undertaken on steel corrosion in concrete, it is more focused on reinforcing steel than on prestressing steel. Although the underlying corrosion science is the same for both, the applicability of data on corrosion obtained from reinforcing steel to prestressing steel needs proof due primarily to the mechanical and physical differences between the two, in particular, the high level of stresses in prestressing steel strands and the microstructure of prestressing steel strands. Research (see above references) has suggested that the corrosion can accelerate if the corroding steel is under high level of stress but this important phenomenon has not been investigated thoroughly, in particular, little research has been undertaken on the corrosion propagation of the prestressing steel in concrete. Moreover, both laboratory tests and field surveys suggest that the effects of corrosion on structural behaviour in RC and PC structures are different, with the latter having less concrete cracking but more serious structural collapses, which are primarily caused by pitting corrosion of prestressing steels in concrete. Therefore, there is a clear and justified need to study the characteristics of pitting corrosion in PC structures, in particular, its propagation and effect on structural capacity. The need is more convincing in the fact that a certain degree of corrosion is necessary before the prestressing steel fails by either mechanism of SCC or pitting corrosion. It is in this regard that the present paper investigates the corrosion propagation of prestressing steel strands in chloride environment.

3. Experimental program

To investigate the corrosion propagation of prestressing steel strands in concrete, a long term observation is essential. For this purpose, an experimental program was designed and undertaken in laboratory. The details of the experiment are as follows.

3.1. Materials of specimens

The commercially available prestressing steel strands of $\phi^{s}12.7$ (1×7) 1860, with ultimate tensile strength $f_{ptk} = 1860$ MPa, were used in the experiment to ensure the practical application of the

results produced. The chemical composition of the prestressing steel is shown in Table 1. For the purpose of comparison, ordinary reinforcing steel bars were also used in the experiment. Again, the commercially available hot-rolled deformed steel bars of $\phi 14$ HRB335, with yield tensile strength $f_{yk} = 335$ MPa, were used in the experiment. The chemical composition of the deformed steel bar is shown in Table 2.

Concrete with grade C30 was used in the experiment. The cement used in concrete was Type 32.5 Portland cement and the aggregates were fine river sand and crushed stone with particle size of 10–15 mm. Tap water was used to mix the concrete. The mixture proportions of the concrete are shown in Table 3.

3.2. Design and construction of specimens

A concrete prism with the dimension of 1000 mm (length) \times 300 mm (height) and 200 mm (width) was used as the test specimens as detailed in Fig. 2. Due to the limited space of the climate-controlled chamber, only six specimens were constructed with a combination of different levels of prestressing and chloride contents in concrete as shown in Table 4. All specimens were cast in the laboratory to ensure a reasonable and consistent quality. The specimen was designed to be constructed in three steps as follows.

Firstly, concrete that was mixed with chloride was cast to a mould with dimension of 1000 mm long, 300 mm high and 200 mm wide, in which a slot of 400 mm long, 120 mm high and 160 mm wide was preset at the centre of the mould, shown as 1st cast in Fig. 2. On each end of the slot, a duct of 20 mm diameter was preset for prestressing steel strands. Then the concrete was cured for 28 days, after which, three steel bars were placed in the slot and prestressing strands in the duct. The prestressing force was applied by jacking the steel strands. To reduce the prestress loss in anchoring due to the short length of the specimen, a technique of double jacking was used (details of this technique are published in Li et al. (2008c)) with the same prestressing forces, which were 150 kN ($0.815f_{ptk}$) for Specimens CRO1 and CRO4, 110 kN ($0.598f_{ptk}$) for CRO2 and CRO5 and 70 kN ($0.380f_{ptk}$) for CRO3 and CRO6. The level of prestressing was ensured by mounting three sensors on steel strands for specimens CRO1, CRO2 and CRO3. The changes of stress in the prestressing strands after the double jacking are shown in Table 5 at different times of the experiment. After anchoring, the duct with prestressing strands was grouted with paraffin to avoid rusting before the test. A conducting wire was welded on each steel strand and bar for corrosion measurement.

Table 1

Chemical composition (wt.%) of prestressing steel strands.

C	Mn	Si	P	S	Cr	Cu	Ni	Ti	Al
0.82	0.74	0.21	0.012	0.006	0.17	0.09	0.03	0.03	0.03

Table 2

Chemical composition (wt.%) of deformed steel bars.

C	Mn	Si	P	S
0.20	1.34	0.55	0.033	0.028

Table 3

Mixture proportion of concrete (kg/m^3).

Water	Cement	Fine aggregate	Coarse aggregate
206	468	632	1107

Secondly, the expansive concrete, which was not mixed with chloride, was cast in the preset slot, shown as the 2nd cast in Fig. 2, to cover the steels so that a natural passivating of the steel could be achieved. The expansive concrete was made by mixing 5% (by cement weight) of a commercially available U-type expansion agent (UEA). Then, the concrete was cured for 2 h. Finally, the rest of the preset slot was filled with expansive concrete, which was also mixed with chloride, up to 10 mm to the surface of the mould, shown as the 3rd cast in Fig. 2. The 3rd cast concrete was cured by water stored in the remaining slot for 3 days. Then the specimens were moved to the climate chamber for long term (53 weeks) exposure to observe the corrosion propagation.

3.3. Test conditions

Since the purpose of the experiment was to investigate the propagation of corrosion, the initiation phase of the corrosion, including chloride ingress, was accelerated by mixing sodium chloride (NaCl) in the concrete. The concentration of chloride ions Cl^- was 0.6% and 3.0% by cement weight respectively. These levels of concentration can ensure the initiation of corrosion before the specimens were exposed to test conditions [28].

The test conditions were simulated in a climate-controlled chamber with an air temperature of $30^\circ\text{C} \pm 2^\circ\text{C}$ and relative humidity of $80\% \pm 5\%$. This condition was selected to represent

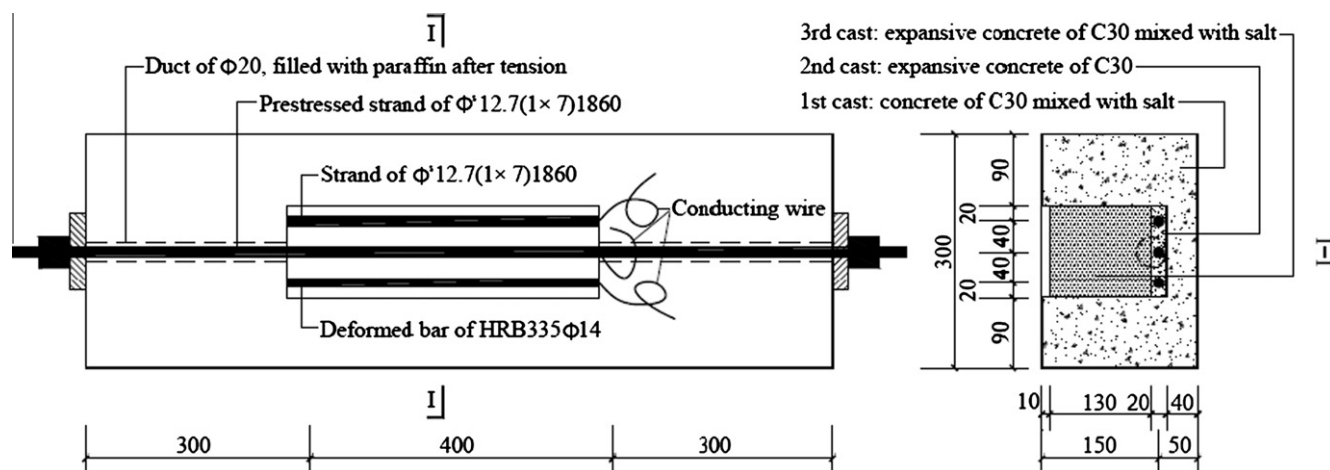


Fig. 2. Details of test specimens (dimension in mm) and cast procedure.

Table 4

Designation of specimens.

Concentration of Cl ⁻	Stress level		
	$\sigma_{pe} = 0.7f_{ptk}$	$\sigma_{pe} = 0.5f_{ptk}$	$\sigma_{pe} = 0.3f_{ptk}$
3%	CRO1	CRO2	CRO3
0.6%	CRO4	CRO5	CRO6

Table 5

Stress (in MPa) variation in samples of prestressed strands.

Time (days)	CRO1		CRO2		CRO3	
	Stress	Stress level	Stress	Stress level	Stress	Stress level
0	1397	$0.751f_{ptk}$	1060	$0.570f_{ptk}$	669	$0.360f_{ptk}$
20	1377	$0.740f_{ptk}$	981	$0.527f_{ptk}$	658	$0.354f_{ptk}$
40	1373	$0.738f_{ptk}$	971	$0.522f_{ptk}$	649	$0.349f_{ptk}$
60	1370	$0.737f_{ptk}$	965	$0.519f_{ptk}$	640	$0.344f_{ptk}$
360	1367	$0.735f_{ptk}$	962	$0.517f_{ptk}$	633	$0.340f_{ptk}$

the climate of the region for practical applications of the test results to be produced. The test conditions were kept constant throughout the test period of 53 weeks.

Four levels of stress were applied to the prestressing steel strands in the specimens. These are $0.7f_{ptk}$, $0.5f_{ptk}$, $0.3f_{ptk}$ and $0.0f_{ptk}$. Ordinary reinforcing steel bars were also placed in the specimens for comparison of corrosion with stressed and unstressed steel strands.

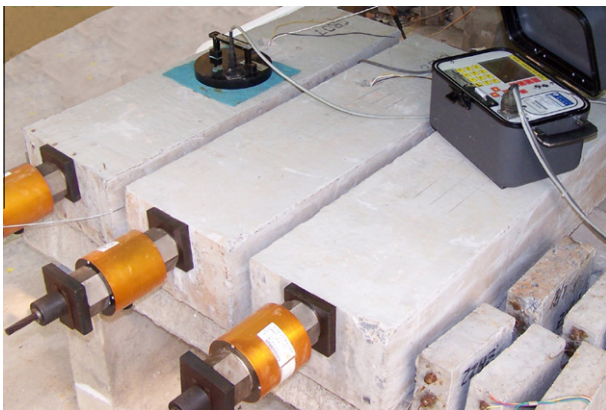
3.4. Measurement of corrosion

Corrosion of the steels in the specimens was monitored constantly in the climate chamber and the corrosion current density, i_{corr} , of both the prestressing strands and steel bars was measured weekly using GECOR8 (see Fig. 3), a commercially available device for corrosion rate measurement based on polarization resistance technique. To ensure the accuracy of the measurement, a guard ring of the diameter of 11.5 cm was used to clearly define the surface area of the corroding steel. It was found that with the guard ring the measurement of corrosion rate was more stable and quicker.

4. Experimental results and analysis

4.1. Corrosion for different levels of prestressing

The corrosion rate, as a function of time and measured by corrosion current density, i_{corr} , for different levels of prestressing, is

**Fig. 3.** Measurement of corrosion rate with GECOR8.

shown in Fig. 4. It needs to be noted that the actual surface area A which has considered the ribs and indentment of both deformed steel bars and prestressing strands was used in the calculating the corrosion current density i_{corr} . It is clear from the figure that the general trend is that the higher the level of prestressing the greater the corrosion rate albeit certain degree of variations exists. This is the case for both levels of chloride content in concrete as shown in Fig. 4a and b.

To gain physical meaning of the corrosion rate, raw data from the measurement, i.e., corrosion current density i_{corr} , are processed as follows. The measured corrosion current density for each type of steel over the test period of 53 weeks was converted to an accumulative weight loss during the period, relative to original weight, using Faraday's law:

$$\rho_{c,y} = \sum \rho_{c,w} = \sum \frac{i_{corr} \cdot A \cdot t_w \cdot M / (|z| \cdot F)}{\rho_l \cdot l} \quad (1)$$

where, $\rho_{c,y}$ is the weight loss relative to original weight in 53 weeks, $\rho_{c,w}$ is weight loss in one week, i_{corr} is corrosion current density measured weekly, in A/cm², A is surface area of corroding steel within the guard ring of GECOR8, in cm², t_w is time of one week in s, M is the atomic mass of Fe, being 56 g, z is atomic charge, being 2 for anodic reaction, F = Faraday constant, being 96,485 C/mol, ρ_l is linear density of steel, in g/m and l is the length of steel within the guard ring of GECOR8, in m.

From a structural engineer's point of view, it is more useful to know the reduction of the diameter of the reinforcing steels (strands and bars). For this purpose Eq. (1) is converted in terms of diameter reduction, ρ_d as follows:

$$\rho_d = 1 - \sqrt{1 - \rho_{c,y}} \quad (2)$$

From Eqs. (2) and (3), the relative weight loss and diameter reduction of the corroded steel strands and bars in 53 weeks were calculated and shown in Table 6. From the table, it can be seen that the relative weight loss of prestressed strand in CRO1 (stress is 1367 MPa) is 1.30 times the average weight loss of unstressed strands in specimens CRO1 to CRO3 (with 3% Cl content), and that the relative weight loss of prestressed strands in CRO4 (same level of stress) is 1.32 times to the average weight loss of unstressed strands in CRO4 to CRO6 (with 0.6% Cl content). These results suggest that, for a given level of chloride content, the corrosion rate of prestressing strands increases with the increase of the level of stresses applied.

4.2. Corrosion for different types of steel

The corrosion rate for different types of steel, i.e., strands and bars is shown in Fig. 5 (where strands were not stressed, i.e., $0.0f_{ptk}$ so that the results are comparable). As can be seen from the figure, there is more corrosion for bars than for (unstressed) strands.

A more quantitative analysis of Table 6 shows that the average relative weight losses of unstressed strands and steel bars in specimens CRO1 to CRO3 are respectively 0.386% and 0.514% with the latter being 1.33 times the former. The average relative weight loss of unstressed strands and steel bars in CRO4 to CRO6 are respectively 0.142% and 0.180% with the latter being 1.29 times the former. These results suggest that the corrosion rate of steel bars is faster than that of unstressed strands under the same conditions. This is considered to be due to the higher quality of passive film on the surface of steel strands than that of deformed steel bars. As a result, it is more difficult for corrosion to initiate on strands than on bars under the same conditions.

The high quality of passive film on the surface of steel strands stems from higher carbon content than that of deformed steel bars as shown in Tables 1 and 2 and smoother surface as from manufac-

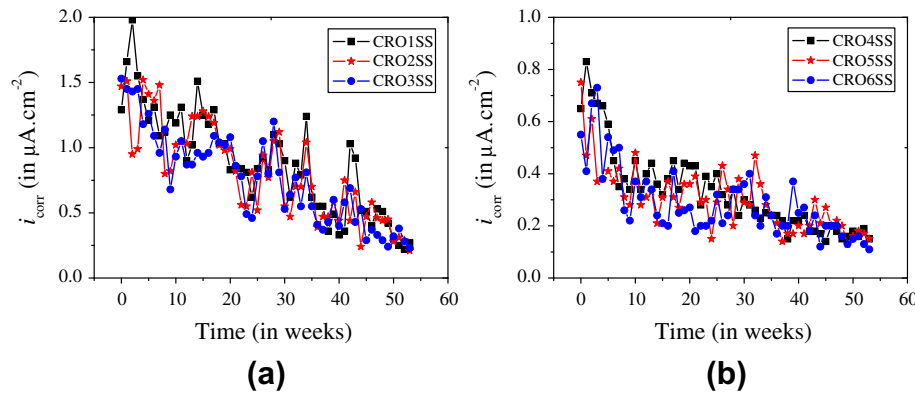


Fig. 4. Corrosion rate for different levels of prestressing: (a) with 3% Cl^- and (b) with 0.6% Cl^- (SS denotes prestressed strands and CRO1SS denotes prestressed strands in specimen CRO1 and so on).

Table 6

Relative weight loss and diameter reduction (in%) of corrode strands and bars in 53 weeks.

Specimens	Prestressed strands	Unstressed strands	Average of unstressed strands	Deformed bars	Average of deformed bars
CRO1	0.501/ 0.251	0.395/ 0.198	0.386/ 0.193	0.525/ 0.263	0.514/ 0.257
CRO2	0.459/ 0.230	0.385/ 0.193		0.514/ 0.257	
CRO3	0.432/ 0.216	0.378/ 0.189		0.504/ 0.252	
CRO4	0.188/ 0.094	0.149/ 0.075	0.142/ 0.071	0.184/ 0.092	0.180/ 0.090
CRO5	0.169/ 0.085	0.142/ 0.071		0.179/ 0.090	
CRO6	0.162/ 0.081	0.135/ 0.068		0.177/ 0.089	

ture. It is known that higher carbon content provides more corrosion cathodes [29] so that more passivating reactions occur. The smoother the strands surface is the finer and firmer the passive film would be both chemically and physically. These micro-structural characteristics of the strands result in a better quality of passive film than those of the deformed steel bars and less corrosion initiation, i.e., fewer corrosion cells [8,9].

4.3. Corrosion for different levels of chloride content

The corrosion rate of prestressing strands and deformed steel bars for different levels of chloride content is shown in Fig. 6. As

can be seen higher chloride content leads to greater overall corrosion rate, given other conditions the same. These results make sense since it is chloride that induces the corrosion regardless it is prestressing or reinforcing steel.

The results of Table 6 show that, with the increase of Cl^- concentration, the relative weight loss increases too. For example, an increase of Cl^- concentrations from 0.6% in specimens CRO4, CRO5 and CRO6 to 3% in specimens CRO1, CRO2 and CRO3, i.e., 5 times increase, results in 3 times difference in relative weight loss. As it is known, although the major role of chloride is to break down the passive film, more chlorides initiate more corrosion and hence increase the overall corrosion rate, given the sufficient supply of water and oxygen. Also chloride ions can absorb moisture which provides sufficient water content in concrete and then increases the corrosion rate [30].

5. Observations and discussions

Based on further study of the characteristics of corrosion and the effects of testing variables on corrosion rate, i.e., the level of prestressing, the type of steels, as well as the concentration of chloride, the following points are worth noting.

5.1. Characteristics of corrosion

The experimental results presented in the previous section, i.e., Figs. 4–6 and Table 6 show that, under the conditions of constant temperature and relative humidity, the corrosion rate of all steel strands and bars decreases over time in a nonlinear manner in

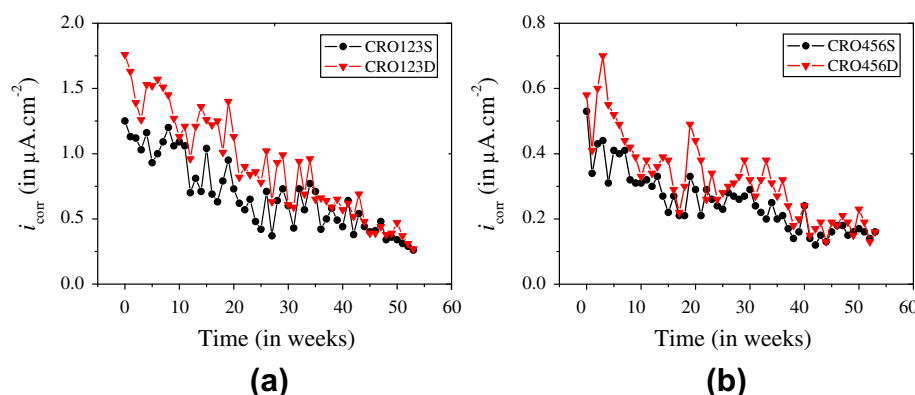


Fig. 5. Corrosion rate for different types of steel (S denotes unstressed strands; D denotes deformed steel bar; CRO123 denotes average value of specimens CRO1, CRO2 and CRO3; same for CRO456).

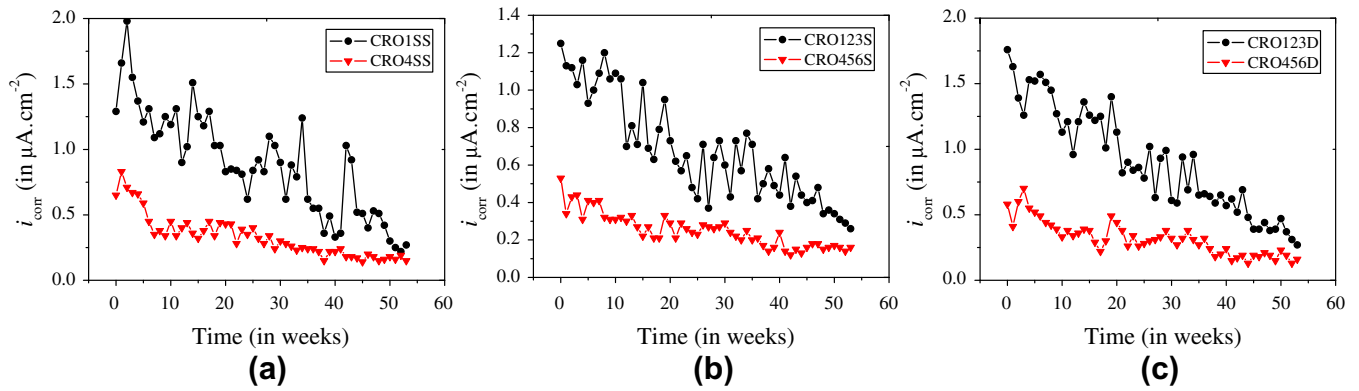


Fig. 6. Corrosion rate for different levels of chloride content (3% Cl content in CRO123 and 0.6% in CRO456).

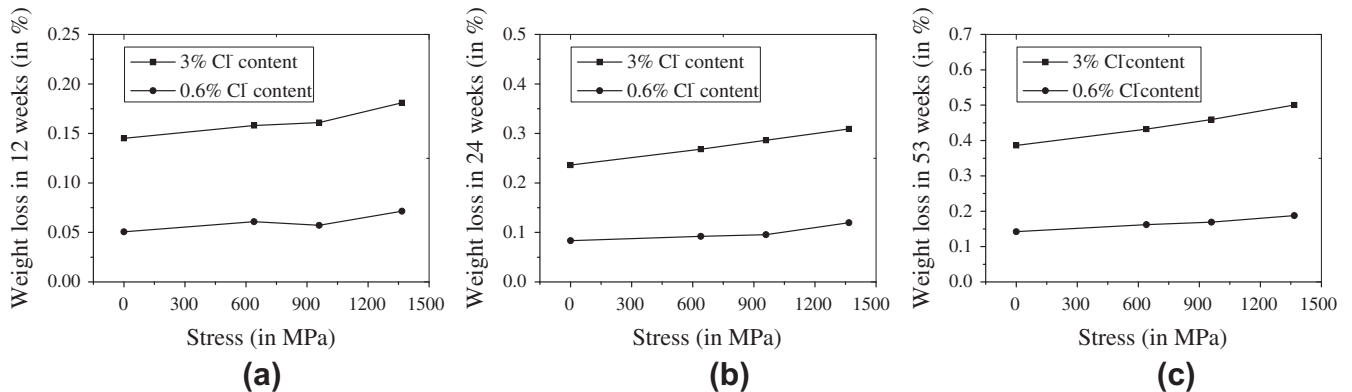


Fig. 7. Effect of stress level in prestressing strands on corrosion rate at different times.

general; more rapidly in the initial stage of the exposure and slowly thereafter. This can be explained as follows.

As it is well known, water (as well as oxygen) plays an important role in the process of steel corrosion in concrete [31]. Whilst cathodic reaction consumes water in the corrosion process it only demands a small quantity. A large proportion of the available water in concrete pores is taken to maintain an aqueous electrolyte (concrete) for the reaction products Fe^{2+} and OH^- to be transported between the anode and cathode. When there is sufficient water in concrete pores, Fe^{2+} and OH^- on the surface of the anode and cathode can enter the pore solution more easily because of their low concentration and hence the reactions of the anode and cathode are faster, which leads to higher corrosion rate. Of course, as it is also known, if there is too much water (for instance, being saturated), the oxygen supply becomes a problem which prevents the corrosion from growing.

In the initial period of the experiment, there was sufficient mixing water in concrete pores which resulted in higher corrosion rate as described above. During the experiment, the mixing water was consumed and some of it may evaporate which resulted in the decrease of the corrosion rate. Moreover, in the process of corrosion, the corrosion products (for instance, red rusts) could fill the pores near the steel surface gradually [32], which reduced the pore water and again led to the decrease of the corrosion rate. Apparently, the evaporating rate and the filling rate became slower over time and hence the decrease rate of corrosion rate was slower correspondingly, as shown in Figs. 4–6.

5.2. Effect of different levels of prestressing on corrosion rate

The effect of stress level in steel strands on corrosion rate is further analysed and shown in Fig. 7, where the values are average of

three specimens with the same chloride content in concrete. As can be seen, with the increase of stress, corrosion rate increases accordingly, and in an approximate linear manner. This can be explained theoretically as follows. According to the theory of mechanics chemistry, mechanical actions can contribute to the negative increase of the equilibrium potential at anode, as described by the following equation [12]:

$$\Delta\phi_{a,r}^{\sigma} = -\frac{\Delta PV}{zF} \quad (3)$$

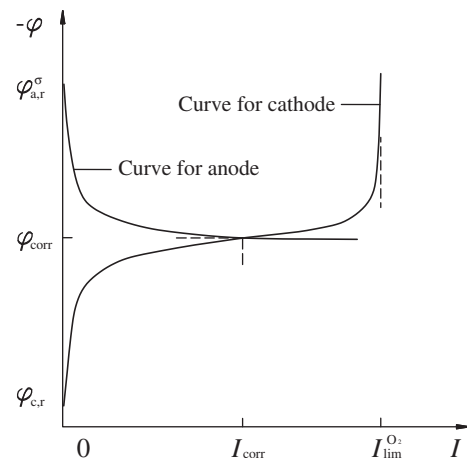


Fig. 8. Polarization curves for steel corrosion (ϕ and I are respectively the potential and current of electrode; $\phi_{a,r}^{\sigma}$ and $\phi_{c,r}$ are respectively the equilibrium potential of anode and cathode; ϕ_{corr} and I_{corr} are respectively the potential and current of corrosion; $I_{lim}^{O_2}$ is the ultimate corrosion current)

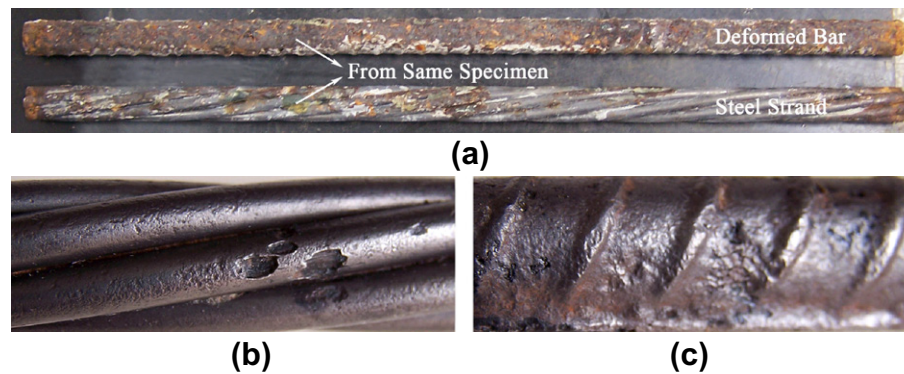


Fig. 9. Corrosion characteristics of: (a) strand and bar, (b) details of strand, (c) details of bar.

where $\Delta\phi_{a,r}^{\sigma}$ is the amount of negative increase of the equilibrium potential at anode due to a mechanical action, e.g., stress σ ; ΔP is the absolute value of hydrostatic pressure at anode (Fe), N/m². For steel bars with uniaxial tensile stress σ , $\Delta P = \sigma/3$. In Eq. (3), V is the molar volume of Fe, being 7.18×10^{-6} m³/mol. It needs to be noted that the negative increase of the equilibrium potential is linearly proportional to the stress σ . As an illustration, take the prestressing strands in specimen CRO1 as an example, where $\sigma = 1367$ MPa, $V = 7.18 \times 10^{-6}$ m³/mol; $z = 2$; and $F = 96,485$ C/mol. From these values, the negative increase of the equilibrium potential at anode is $\Delta\phi_{a,r}^{\sigma} = -17$ mV.

The negative increase of equilibrium potential at anode will lead to the increase of corrosion rate as can be seen from the polarization curves for steel corrosion in Fig. 8 [33]. From the figure it is clear that the corrosion current depends on the intersection point of polarization curves for anode and cathode. When the equilibrium potential at anode increases negatively (due to stress according to Eq. (3)), it means that the whole polarization curve for anode moves upwards. As such, the intersection point, which represents the corrosion current, moves rightwards whilst the polarization curve for cathode remains unchanged (since it is not affected by the stress). This means the corrosion current increases.

5.3. Effect of different types of steel on corrosion rate

It was observed from the experiment, as shown in Fig. 9, that there are fewer corrosion cells on the surface of prestressing strands than that of deformed bars. This reduced number of corrosion cells leads to faster growth of local corrosion at already corroded spots (cells). Since there is relatively more supply and less demand of water and oxygen for a small number of corrosion cells to sustain, pitting corrosion dominates in each strand (wire). In addition, the electrochemical characteristics of pearlites of steel strands can be different for each strand (wire) [34]. For this reason, corrosion may progress differently for each strand. Therefore, for corroded strands, more local and uneven corruptions occur as shown in Fig. 9b (also see [26]).

On the other hand, lower quality of passive film of deformed bars makes it easier for chloride ions to penetrate and initiate corrosion over the whole surface and hence relatively evenly. However, with the increase of corrosion cells, the supply of water and oxygen for corrosion propagation becomes scarce relatively [35]. This is why corrosion of deformed bars is relatively uniform as shown in Fig. 9c.

Unfortunately the polarization resistance measurement (e.g., by GECOR8) provides only an uniform or total corrosion state but it is difficult to detect the pitting corrosion. Also pitting corrosion has lesser corroding area than that is measured and as such the measured corrosion rate is smaller than the actual rate. It appears that

polarization resistance technique may not represent the true corrosion state of prestressing steels in concrete which can be dangerous from a structural point of view since the pitting corrosion will lead to the reduction of load carrying capacity of the structure without being detected. This is perhaps why there are more structural collapses of PC structures without warnings than those of RC structures, which vindicates the need for more research on corrosion propagation of prestressing steels in concrete.

It may be noted that the results produced in the experiment, as further analysed and discussed above, can be useful for practising engineers and asset managers of PC structures in their decision making on potential interventions for the structures. For example, the knowledge that corrosion rate increases with the increase of stresses in an approximate linear manner would help practising engineers and asset managers plan timely maintenance of PC structures when stresses in the structures are expected to increase due to, e.g., additional applied loads. Moreover, the information presented in the paper can raise the awareness of the dangers of pitting corrosion of prestressing steels in PC structures which may lead to collapse without warnings.

6. Conclusions

The propagation of prestressing steel corrosion in concrete subject to chloride attack has been investigated in this paper. A long term experimental program has been presented in which the corrosion of twelve prestressing steel strands and six ordinary reinforcing steel bars was thoroughly examined. The effects of the level of stresses in the steel and the type of steels on corrosion rate have been studied both experimentally and theoretically. It has been found that the corrosion rate of prestressing steel strands in concrete increases in an approximate linear manner with the increase of the level of stresses applied and that the corrosion rate decreases over time initially fast and slowly later. It has also been found that the pitting corrosion is the main form of prestressing steel corrosion in concrete under chloride attack and that the corrosion rate as measured by polarization resistance technique may not represent the true corrosion state of prestressing steel strands in concrete. The information presented in the paper can be useful for practising engineers and asset managers of prestressed concrete structures in their decision making on potential interventions for the structures. It can be concluded that the corrosion of prestressing steel poses higher risk than that of reinforcing steel from a structural point of view. Evidently, more research on corrosion of prestressing steel in concrete is urgently needed to provide better understanding and knowledge in the management of prestressed concrete structures so that unexpected structural collapses can be prevented.

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