CATHODIC PROTECTION OF STEEL IN CONCRETE - EFFECT OF STEEL SURFACE AREA ON OXYGEN TRANSPORT THROUGH SUBMERGED CONCRETE

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ABSTRACT

The oxygen transport through submerged mortar specimens with varying amounts of embedded steel has been measured. The measurements were made by recording the current for reduction of oxygen at the embedded steel.

It was found that the surface area of steel embedded beneath a given mortar surface had only a slight effect on the oxygen reduction current. For potential values between -850 mV and -500 mV (SCE) the applied potential has very little effect on the oxygen reduction current.

Key words: Concrete, cathodic protection, oxygen transport, embedded steel area, potential

1 INTRODUCTION

On concrete structures exposed to sea water two types of corrosion may occur, corrosion of steel embedded in concrete and corrosion of steel components exposed to sea water. The main controlling factor for corrosion of embedded steel is the reduction of oxygen at the embedded steel surface. At the steel surface oxygen is consumed by the cathodic reaction that is necessary for the corrosion process to proceed. Also for situations when corroding exposed steel components are galvanically connected to the reinforcing steel system, reduction of oxygen at the steel surface will be of major importance to the corrosion of the exposed steel.

On all offshore concrete structures in the North Sea the external integrated steel components are cathodically protected by means of sacrificial anodes. The main output of these anodes, however, is not consumed by the protection of the external steel components but by the oxygen reduction at the electrically connected reinforcing system of the structure. This oxygen reduction at embedded steel causes a current drainage that may account for the main output of the protection system.

It has earlier been shown that the temperature has a substantial effect on the oxygen reduction at steel embedded in concrete /1/. A temperature increase from 1 °C to 30 °C causes an increase in current density from the reduction process from 0.5 to 1.2 mA/m^2 steel surface.

It was also shown that the rate limiting step in the overall process of oxygen diffusion through wet concrete and electrochemical reduction at embedded steel was diffusion of oxygen through the concrete.

Data on oxygen flux through concrete are earlier reported /2/ ranging between 1.9 and 14,8x10^{-9} mole/m^{2}sec /2/ and diffusivities between 3 and 10x10^{-10} m^2/sec for concretes with 100% RH /3/ and between 1 and 3x10^{-12} m^2/sec for cement pastes /4/.

For long term polarization test of steel embedded in concrete piles /5/ a typical current density of 1 mA/m^2 steel surface is obtained for steel in concrete piles in wet soil and sea water.

Several authors have discussed current requirements for cathodic protection of embedded steel /6, 7, 8/. The requirements cited vary between 0.4 and 4 mA/m^2 steel surface depending mainly on the concrete quality.

In a study of galvanic current between embedded steel and corroding exposed steel /9/ a value of about 25 mA/m^2 has been found for an area ratio of 10^6 between embedded and exposed steel.

In order to get information about the influence of the amount of embedded steel on the current drainage some laboratory experiments have been undertaken.

2 EXPERIMENTAL

2.1 Principle

The measurements are based on the principle that when a negative potential (within certain limits) is applied to steel embedded in concrete the only cathodic reaction taking place[1] is reduction of oxygen at the steel surface:

$$1/2\ O_2 + H_2O + 2e = 2OH^- \qquad (1)$$

Therefore, by applying a constant negative potential to an embedded steel plate the oxygen transport (or rather the rate of oxygen reduction at the steel plate) through the concrete may be recorded as an electrical current.

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[1] Reduction of chromates or other cations present in the concrete is not considered

By applying Faraday's law the mass transport per unit time(Flux) and - according to Fick's 1. law - the diffusion constant can be calculated:

$$J = \frac{I_{steady-state}}{n \times F} \qquad (2)$$

$$J = -D\frac{dC}{dx} \qquad (3)$$

where:

J = Flux	(mole/m^{2}s)
I = Current density	(A/m^2)
n = Valence	(2)
F = Faraday constant	(Asec)
D = Diffusion constant	(m^2/s)
C = Concentration	(mole/m^3)
x = Distance	(m)

2.2 Test specimen

The specimens were produced by embedding a mild steel plate within a PVC form with diameter 11 cm and height 4 cm. An insulated copper wire was connected to the steel plate by means of a copper nail. The PVC form served both as mould during casting and insulation during the test. The casting was made by half filling the plastic mould with mortar, vibrating on a vibrating table until a smooth surface was obtained, positioning the steel plate, filling up with mortar and vibrating again.

Two sets of specimens were made; one set with area ratios A_{steel}/A_{mortar} varying from 0.066 to 1 and another set with the area ratios varying from 1 to 11.

In the first set of specimens the area of the embedded steel was varied by embedding steel plates with varying diameters in the mortar. In the other set of specimens the area of the embedded steel was varied by vertically connecting to a steel plate of diameter 9 cm different lengths of a 2.5 cm broad steel strip. An example of this type of steel elctrode is shown in figure 1.

The cement was a Standard Portland Cement and the mortar composition was 1 : 2 (cement : sand by weight) and water to cement ratio of 0.5.

After casting the specimens were cured for 24 hours at 100% RH and then water cured for 2 months at 22°C.

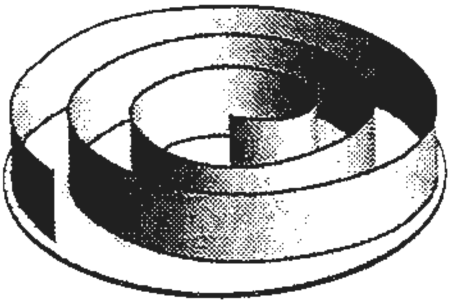

Fig. 1 Example of steel electrode for specimens with ratio A_{steel}/A_{mortar} larger than 1

2.3 Procedure

The experimental set-up is identical to what has earlier been reported /1/. The test specimens, stainless steel counter electrode, salt bridge connected to the reference electrode and glass sinter tube for air bubbling were placed in a water-filled plastic container. Some of the experiments were made at temperatures other than room temperature. For these experiments the container with specimens were placed in an environmental chamber.

The embedded steels were coupled to a potentiostat and a constant potential was applied to the embedded steel electrodes until a steady-state-current was obtained. At steady-state the oxygen reduction current for each specimen was recorded by measuring the potential drop through a 10-ohm resistor.

In the experiments the applied potential was varied between -450 and -850 mV (SCE). Before a potential change it was necessary to wait up to two months before the current became stable.

3 RESULTS AND DISCUSSION

3.1 Specimens with area ratios 1 or less

The results for the test series with area ratios of 1 or less and temperature 20 °C are presented in Table 1. The data are presented as current densities based on area of mortar surface.

The table clearly shows that the surface area of steel embedded beneath a given mortar surface has little effect on the amount of oxygen that is reduced at the steel surface. The results seem to show only a slight increase in the oxygen transport through the concrete when the area ratio of embedded steel to mortar surface increases from a very low value to 1.

The values of the mean current densities also suggest the oxygen transport to be only slightly decreased when the applied potential is reduced from -850 to -500 mV (SCE).

Table 1. *Current densities (µA/m² mortar) for oxygen reduction with various area ratios* A_{steel}/A_{mortar}.

Area ratio	Current density (µA/m² mortar) vs applied potential (mV SCE)				
	-850	-800	-700	-600	-500
0.066	280	269	244	221	216
0.100	141	280	209	221	166
0.125	228	100	72	75	61
0.250	353	249	244	244	237
0.500	345	317	298	279	196
1.000	343	345	322	335	288
Mean current density	269	260	231	229	194

3.2 Specimens with area ratios 1 or more

For this type of specimens the time necessary for the currents to become stable was longer than for the other type of specimens. The scattering of the data was also greater as shown in Table 2 where the values recorded at 20°C are shown.

Table 2. *Current densities (µA/m²mortar) for oxygen reduction with various area ratios* A_{steel}/A_{mortar}.

Area ratio	Current density (µA/m²mortar) vs applied potential (mV SCE)			
	-850	-750	-700	-650
1	326	370	97	53
2	253	130	157	253
3	284	147	41	318
4	232	193	134	231
5	275	162	100	123
6	347	125	128	168
7	423	125	130	188
8	262	225	85	2947*
9	130	87	118	169
10	162	206	87	182
Mean current density	269	260	231	229

** Not included in the mean value*

Also this table show, however, that the effect of both area ratio and of applied potential is small. By increasing area ratios it seems to be a slight decrease in the oxygen reduction current. When the potentials are reduced from -850 to -650 mV (SCE) a slight decrease in the current is observed.

For another set of specimens of this type the oxygen reduction current was measured at the temperature of 1, 20 and 30 °C. The applied potential was -600 mV (SCE). The results are presented in Table 3.

Table 3. Effect of temperature and area ratio between embedded steel surface and concrete surface on current densities (µA/m2) for reduction of oxygen on embedded steel.

Area ratio	Current density (µA/m^2) vs temperature		
	1 °C	20 °C	30 °C
1	273	469	605
2	1670	1834	2713
3	774	3331	3365
4	1802	2468	2615
5	508	431	1214
6	360	703	1025
7	529	439	765
8	253	365	415
9	1072	243	859
10	196	302	394
11	160	307	336
Mean current density	689	985	1291

For these specimens the values scattered very much and the mean values are higher. The observed effect of temperature, however, fits very well with other observations /1/.

4 CONCLUSIONS

1. The oxygen reduction current at embedded steel is very slightly influenced by the steel surface area that is embedded beneath a given concrete surface.

2. When the area ratio of steel surface to concrete surface is increased from a very low value up to 1 a slight increase in the oxygen reduction current is observed.

3. When the area ratio of steel surface to concrete surface is increased from 1 to 10 a slight decrease in the oxygen reduction current is observed.

4. Based on the above observation is concluded that the oxygen reduction current at embedded steel is controlled by the diffusion of oxygen through the bulk of concrete.

5. When embedded steel is polarized to potentials between -850 and -500 mV (SCE) the oxygen reduction current is nearly independent of the applied potential.

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