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**CORROSION MEASUREMENTS ON REINFORCEMENT IN
SILICA FUME CONCRETE**

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الخلاصة :

يعتبر صدأ (تآكل) حديد التسليح سبباً مهماً للتلف التدريجي الذي يحدث في التراكيب الاسمنتية . نعرض في هذا البحث جهازاً تم استخدامه في جامعة ليدز لدراسة هذا التلف ، وذلك بقياس المقاومة الخطية المستقطبة . ثم نوظف ذلك لاختبار خلطات الاسمنت وللتنبؤ بأدائها في حماية حديد التسليح . تتطلب هذه القياسات عناية خاصة للتأكد من أن نتائج القياس لم تتأثر بقيمة السعة الكهربائية أو بمقاومة أسلاك التوصيل أو القيمة المقابلة للاسمنت . وللتغلب على هذه المعضلة ، قُمنّا بتأخير زمن القياس بمقدار ٣٠ ثانية وذلك لتقليل كلٍ من المقاومة والسعة الكهربائية . ثم نقوم بطرح قيمة السعة الكهربائية والمقاومة للاسمنت من النتائج .

وللحصول على نتائج معملية قمنّا بتسريع عملية تآكل حديد التسليح بوضع عينات الاسمنت في وسط ملحيّ وتحت تأثير جهد كهربائي . تشير النتائج إلى أن الاسمنت الرغوي ذي أداء أفضل من الاسمنت البورتلاندي العادي .

ABSTRACT

Corrosion of reinforcement is a major cause of deterioration of concrete structures. Linear polarization resistance measurements can be used to test different concrete mixes to predict their performance in protecting the steel in structures. An apparatus to carry out these measurements on concretes containing silica fume has been used at Leeds.

When carrying out linear polarization measurements care must be taken to ensure that the readings are not disrupted by the capacitance of the interface and the resistance of the concrete. In this project a time delay of 30 seconds was used to reduce the effect of the capacitance and the resistance of the concrete was measured separately and subtracted.

In order to obtain results in laboratory time scales it is necessary to accelerate the corrosion. In this project the concrete samples were placed in a salt solution and an anodic voltage was applied. The results show that under these conditions the silica fume concretes performed better than the ordinary portland cement control concretes.

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CORROSION MEASUREMENTS ON REINFORCEMENT IN SILICA FUME CONCRETE

INTRODUCTION

Corrosion of the reinforcement is a major cause of deterioration of concrete structures. Silica Fume (SF) is currently being used as a cement replacement material and the experiments described in this paper are intended to provide further information on the extent to which SF can prevent this deterioration.

The method used to measure the corrosion is based on a simple sample geometry (Figure 1) in which an electrical circuit is established from a steel bar through concrete and to a salt solution. The experiments measure the potential of this system in open circuit and its impedance when a voltage is applied.

THE METHOD OF LINEAR POLARIZATION RESISTANCE MEASUREMENT

The model used for this analysis assumes that corrosion of steel in concrete depends on two processes which are arranged as in Figure 2. Details of the chemical processes are frequently quoted in the literature and show that iron atoms are lost from the steel at the anode and the oxygen reduction occurs at the cathode. As the reactions occur electrons are liberated in the steel at the anode and combine at the cathode thus causing current to flow in the direction shown. If both processes are in the same area this is a micro circuit but they can be well separated to give a macro circuit. For example at sea level on a marine structure the cathode may be in the splash zone and the anode below the water level. If a structure is not submerged macro circuits will be severely limited by the connection between the two processes which must pass through the concrete resistance. Linear polarization measurements are usually only relevant to micro circuits.

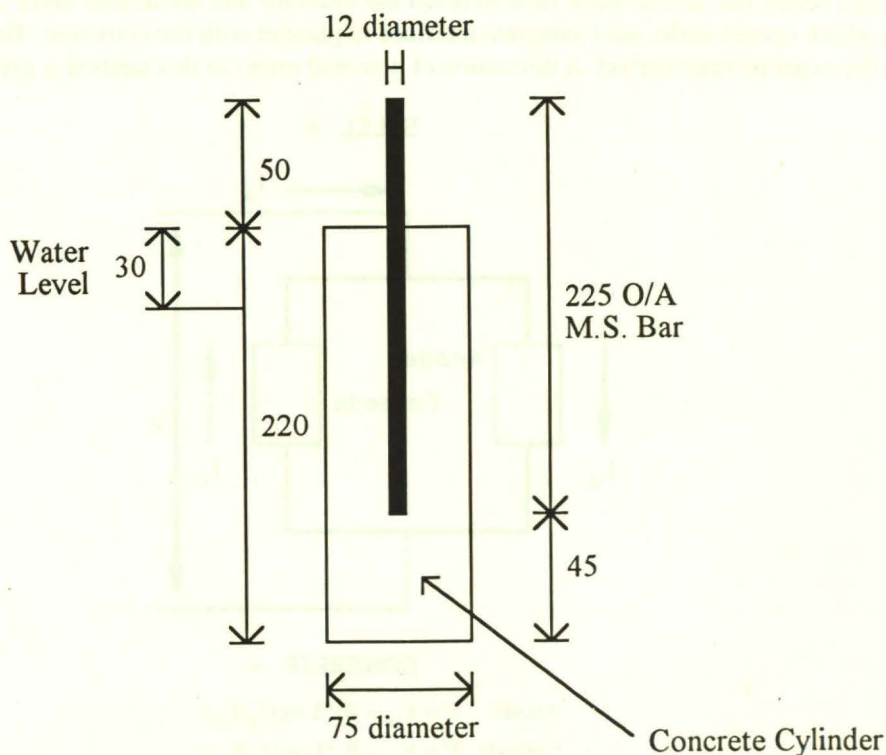


Figure 1. Section Through Corrosion/Resistivity Specimen.

The condition of this circuit which is of most interest for this analysis is when there is no external circuit and the external current I_x is zero and the voltage V across the circuit is equal to the rest potential E_0 . This is the condition which would normally occur in a structure in service and in this condition the current which flows around the loop is the corrosion current I_{corr} . It may be seen from Figure 2 that if there is no external current the anodic current I_a is equal to the loop current I_{corr} . Thus, a measurement of I_{corr} may be used to calculate the rate of loss of iron atoms at the anode, *i.e.* the corrosion rate. The full analysis of the circuit near the rest potential was published by Stern and Geary [1].

By assuming logarithmic voltage-current relationships at the anode and the cathode Stern and Geary derived the relationship:

$$I_{\text{corr}} = B/R_p,$$

where R_p is the polarization resistance and is equal to $(V-E_0)/I$ which is the gradient of the voltage-current relationship and B is a constant. A value of 26mV is normally used for B [2]. The effect of this analysis is shown graphically in Figure 3. The two currents I_a (anodic) and I_c (cathodic) each depend logarithmically on voltage but the net current I_x follows a linear relationship at voltages near E_0 .

THE EQUIVALENT CIRCUIT

Unfortunately the measurements are not as simple as would appear from the above analysis, because of the effects of other parts of the system. The performance of the total system is most easily explained by using an equivalent circuit. This is a circuit of linear electronic components which give the same voltage-current relationship as the steel in concrete. The corroding interface has been seen above to have a linear voltage-current relationship but not one which gives zero current at zero applied voltage. It is thus equivalent to a resistor and a voltage step in series.

The resistance R_p and voltage step E_0 may be seen in the circuit which is shown in Figure 4. The other two components are the concrete resistance and the double layer capacitance. The concrete resistance represents the concrete through which the current must flow to reach the interface and the double layer capacitance represents a second effect which occurs at the steel-concrete interface in parallel with the corrosion. This circuit has been used as a basis for the experimental method. A discussion of potential errors in this method is given in reference [3].

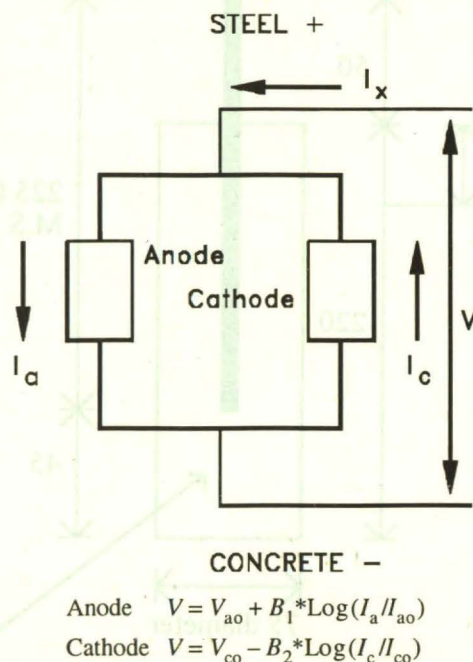


Figure 2. Corroding Steel/Concrete Interface.

EXPERIMENTAL METHOD

Mix Designs

Two SF mixes were tested with water/cementitious ratios of 0.3 and 0.46. These mixes had 20% of the cement replaced by SF supplied by Elkem Chemical from Norway. Two control mixes with the same water/cementitious ratios but made with plain cement were also tested. Details of the mixes are as shown in Table 1.

A naphthalene-formaldehyde condensate superplasticizer was used which made all of the mixes suitable for site use. Mortar was made with the same proportions without the coarse aggregate.

Casting Samples

The concrete samples were cast to the dimensions shown in Figure 1. The mortar samples were of similar proportions but approximately half the size of the concrete samples.

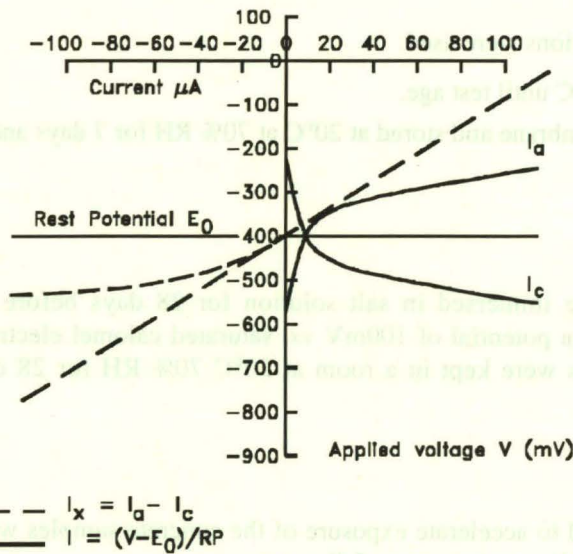


Figure 3. Combination of Anodic and Cathodic Currents

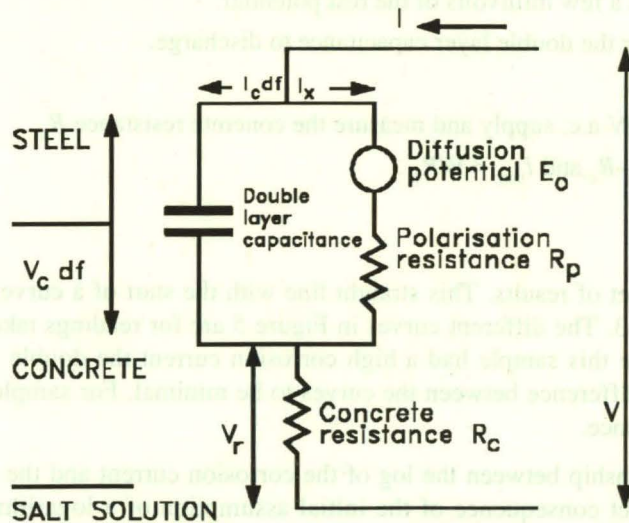


Figure 4. The Equivalent Circuit of Steel in Concrete Used in the Analysis.

Table 1. Mix Designs.

Mix	A	B	C	D
Cement (kg/m ³)	344	430	252	315
Silica (kg/m ³)	86	0	63	0
Water/(cem+silica)	0.3	0.3	0.46	0.46
Superplasticizer (% of c+s)	1.4	1.4	1.9	1.9
5–20 mm aggregate/(c+s)	3	3	4	4
Fine aggregate/(c+s)	1.5	1.5	2.3	2.3
28 day strength (MPa)	113	80	88	55

Curing Conditions

Three different curing conditions were used:

1. Curing in fog room at 20°C until test age.
2. Treated with a curing membrane and stored at 20°C at 70% RH for 7 days and then in water at 6°C.
3. Curing in water at 6°C.

Exposure

The concrete samples were immersed in salt solution for 28 days before testing. In order to make this environment more aggressive a potential of 100mV vs. saturated calomel electrode was applied to them during exposure. The mortar samples were kept in a room at 20°C 70% RH for 28 days and placed in salt solution immediately before testing.

Testing

The voltage which was used to accelerate exposure of the concrete samples was disconnected 24 hours before testing. The test procedure for all samples was as follows:

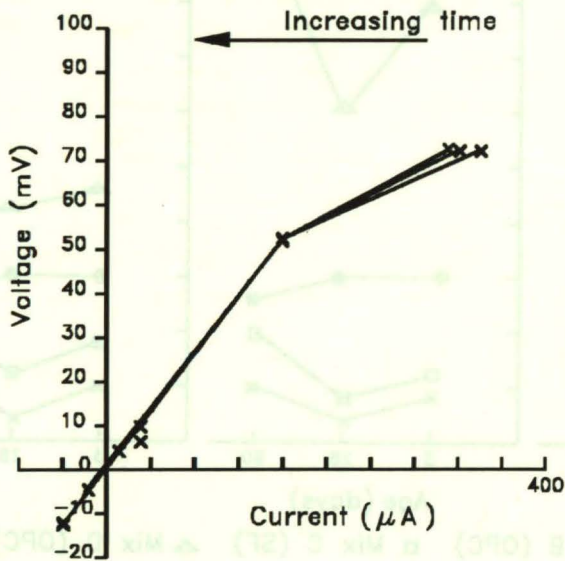
- (a) Measure the rest potential in open circuit.
- (b) Apply a voltage within a few millivolts of the rest potential.
- (c) Wait for 30 seconds for the double layer capacitance to discharge.
- (d) Measure the current I_x .
- (e) Connect a 50Hz, 100mV a.c. supply and measure the concrete resistance R_c .
- (f) Calculate $R_p(V-E_o)/I_x - R_c$ and $I_{corr} = B/R_p$.

RESULTS

Figure 5 shows a typical set of results. This straight line with the start of a curve corresponds with part of the curve for I_x shown in Figure 3. The different curves in Figure 5 are for readings taken at different times after the voltage was applied. Because this sample had a high corrosion current the double layer capacitance discharged quickly and this caused the difference between the curves to be minimal. For samples with low corrosion current there was a substantial difference.

Figure 6 shows the relationship between the log of the corrosion current and the rest potential. A straight line would be expected as a direct consequence of the initial assumption of a logarithmic response of the cathodic process and this graph provides a useful validation of that assumption. It indicates that all samples had similar cathode conditions, *i.e.* the corrosion was under "anodic control".

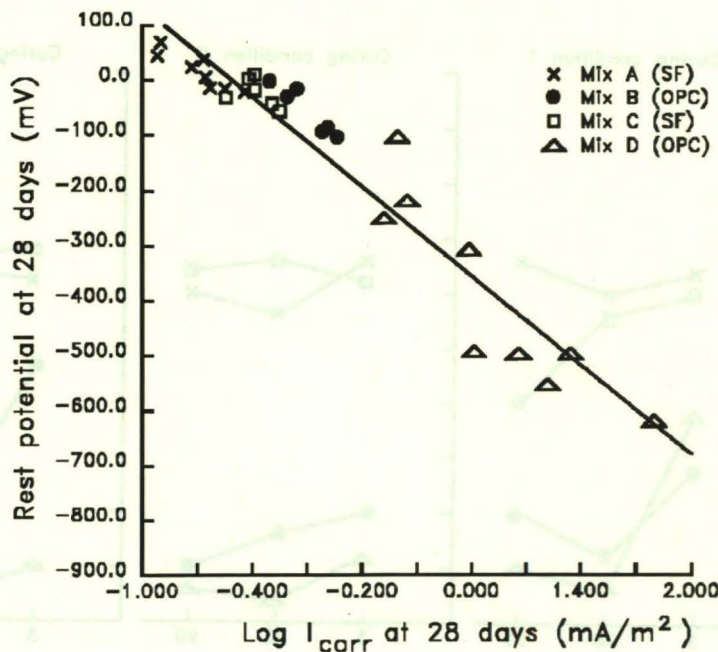
Figures 7 and 8 give the results for the corrosion current and it may be seen that for the concrete samples the SF mixes performed far better but for the mortar samples they were far worse. The concrete samples are considered to be more representative of conditions likely to be found in a structure and from them it is concluded that SF can be



Sample D1 A.C. Reading X

Mix D (O.P.C., w/c=0.42) the data shows a high corrosion current

Figure 5. Linear Polarization Measurements at 10, 20, and 30 Seconds and Extrapolations to Zero and Infinite Time.



Equation for line: $Y=154.1-272.9X$

$R^2 = 0.925$

Figure 6. Linear Relationship Between the Rest Potential and the Corrosion Current for the Set 2 Samples after 28 Days.

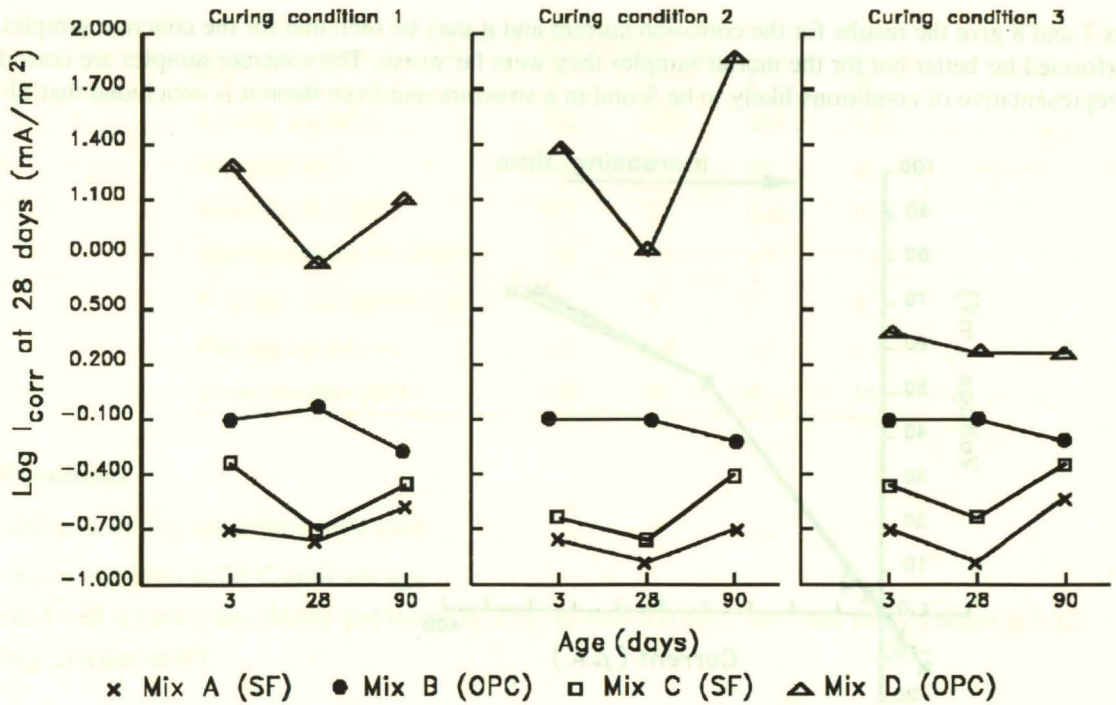


Figure 7. Corrosion Rate for Main (set 2) Concrete Samples after 28 Days Exposure to Salt Solution.

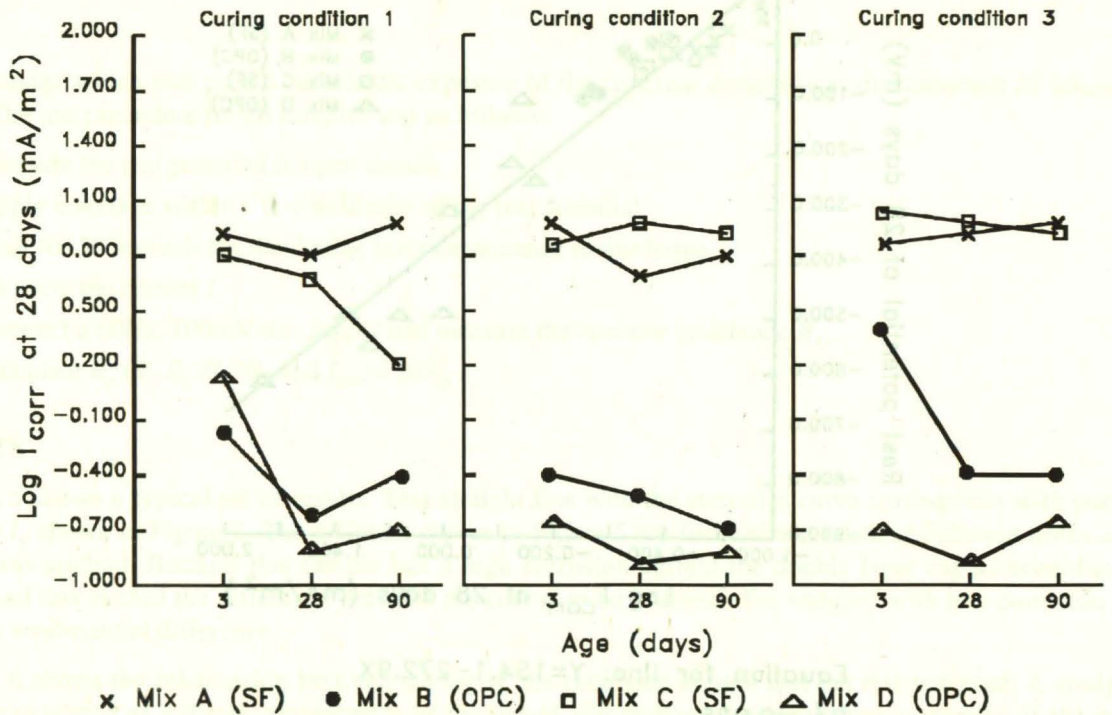


Figure 8. Corrosion Current of Mortar Control Samples when First Exposed to Salt Solution.

used to reduce corrosion. The higher corrosion rates in the mortar samples were caused by some phenomenon related to the drying, possibly a higher water retention in the SF samples due to a lower permeability. Although not representative of the majority of site conditions the treatment of the mortar samples was certainly not extreme (they were used as control samples in a carbonation experiment). The results from the mortar samples therefore indicate that under some circumstances SF can cause increased corrosion rates.

The concrete resistance R_c would be expected to correlate with the corrosion current because it represents a resistance between the anode and the cathode. A statistical evaluation of this has been published [4].

CONCLUSIONS

1. Direct readings of corrosion rates may be obtained from linear polarization measurements, but care must be taken to compensate for the concrete resistance and the double layer capacitance.
2. SF will normally reduce corrosion rates.
3. Under some conditions SF will increase corrosion rates so indiscriminate use is definitely not advised.

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