THE RESISTANCE OF STAINLESS STEEL, PARTLY EMBEDDED IN CONCRETE, TO CORROSION BY SEAWATER

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G. N. Flint* and R. N. Cox†

DEPARTMENT OF THE ENVIRONMENT: BUILDING RESEARCH ESTABLISHMENT

SYNOPSIS

The corrosion resistance of Type 316 stainless steel, partly embedded in concrete, partly exposed to stagnant seawater and partly exposed to flowing seawater, has been determined over various periods up to about $12\frac{1}{2}$ years duration. The exposure tests were carried out in full immersion and tidal conditions, on specially designed concrete blocks. Mild steel specimens were also tested for comparison. Corrosion of exposed stainless steel was localized, not extensive, and affected neither the strength nor ductility of the specimens. Contrary to expectation, crevice corrosion occurred on only one of the 42 test specimens, and only after $12\frac{1}{2}$ years total immersion.

It is considered that the alkalinity of the concrete was responsible for minimizing corrosion on both embedded and external areas of stainless steel. Ordinary Portland cement concrete gave more protection to the stainless steel than did sulphate-resisting Portland cement concrete due, it is thought, to the higher cement content of the former and consequent greater reserve of alkalinity. The higher proportion of tricalcium aluminate in the OPC concrete and its known effect in complexing chloride ions and delaying their ingress into concrete was also considered to be of great significance.

Introduction

The behaviour of steel reinforcing bars embedded in concrete when exposed to marine and other chloride-containing environments is well documented (see for example, Ref. 1). It has been shown that excellent performance of reinforced concrete in such environments can be achieved provided that the concrete cover over the reinforcing steel is sufficiently thick, say, 50 mm, and is well compacted. Under these circumstances, penetration of chlorides to the steel is slow and, even when it occurs, corrosion proceeds slowly because of the limited access of oxygen, high resistivity of electrolyte paths, alkalinity of the concrete and polarization of the steel. If the cover is thin or not well compacted, penetration of seawater soon occurs, and access of oxygen is not significantly restricted, resulting in corrosion of the steel and spalling of the concrete[2].

However, situations occur where only a thin cover of concrete is possible or where fixtures project from the concrete as, for example, in dowels between concrete slabs in roads and runways, and in fixings for plant or machinery. In these situations, it is becoming increasingly common to employ stainless steel, especially where exposure to seawater or de-icing salts occurs and maintenance is difficult or expensive[3].

At the time when the present investigation was initiated, massive concrete constructions were envisaged in the North Sea and the question arose as to the behaviour of stainless steel fixtures immersed in seawater or exposed to tidal action. The few available data were only partly relevant to the situation. It was known that stainless steels, even Type 316, were susceptible to localized corrosion in chloride media, but it was considered possible that the effect of such corrosion on strength could be much delayed. Additionally, it was feared that the concrete/stainless steel interface would provide a narrow crevice, particularly favouring corrosive attack. However, the nature of corrosion on, and the corrosion products generated by, stainless steels are different from those on unalloyed and low alloy steels and conceivably their

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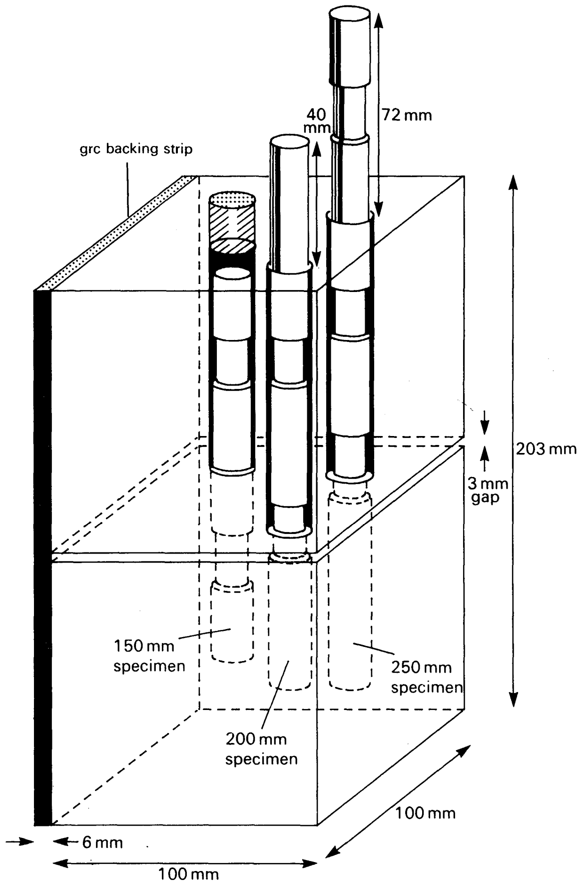

Figure 1: Schematic diagram of concrete blocks showing position of glass-fibre-reinforced cement backing strip and steel specimens.

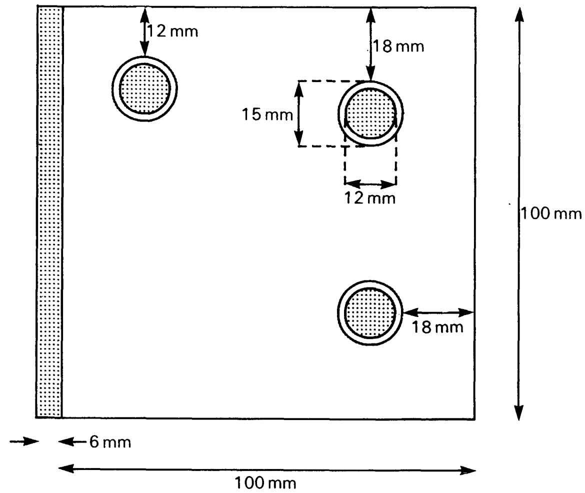

Figure 2: Horizontal section through upper concrete block.

effect on spalling of concrete could be much less. The present investigation was undertaken to provide information on these aspects.

Experimental procedure

GENERAL

The design of specimen for the experiment was dictated by:

(1) the available test material; 12·5 mm diameter Type 316 stainless steel rod (and mild steel rod for comparison);
(2) the experimental facilities;
(3) the need to simulate as accurately as possible crevices and other exposure conditions relevant to both fixtures and reinforcement;
(4) the need to provide variation in the area exposed to flowing seawater since it is well known that corrosion in crevices is promoted by contact with a large external cathodic area[3].

The selected test specimen consisted of a dual concrete block composed of two 100 mm cubes, 3 mm apart, each supported along one face by a 6 mm thick sheet of glass-fibre-reinforced cement (grc). Three steel tensile test specimens were embedded in the lower cube and passed into or through the upper cube with a 1·5 mm gap around them, see Figures 1 and 2. The gap around the bars in the upper cube was formed by means of a steel sleeve which was withdrawn after casting.

TENSILE TEST PIECES

The three tensile test specimens in each dual concrete block were 12 mm in diameter with 20 mm gauge lengths for tensile testing of 9 mm diameter, machined from 12.5 mm diameter rods. The positioning of the gauge lengths in the blocks is shown in Figure 1 and also in Figures 3 to 10. The compositions of the steels are given in Table 1.

CONCRETE

Two concrete mixes were used to produce concretes of similar strength, one containing ordinary Portland cement (OPC) and the other containing sulphate-resisting Portland cement (SRPC). The mix proportions and properties were as follows.

TABLE 1: **Composition of steels.**

Element	Type 316 stainless steel	Mild steel
C	0·046	0·060
Cr	17·07	0·05
Cu	0·17	0·27
Mn	1·68	1·36
Mo	2·79	<0·05
N	0·023	–
Ni	12·18	0·11
P	0·020	0·075
S	0·020	0·037
Si	0·56	<0·05
Fe	Balance	Balance

Figure 3: SRPC concrete blocks after $12\frac{1}{2}$ years continuous exposure to seawater.

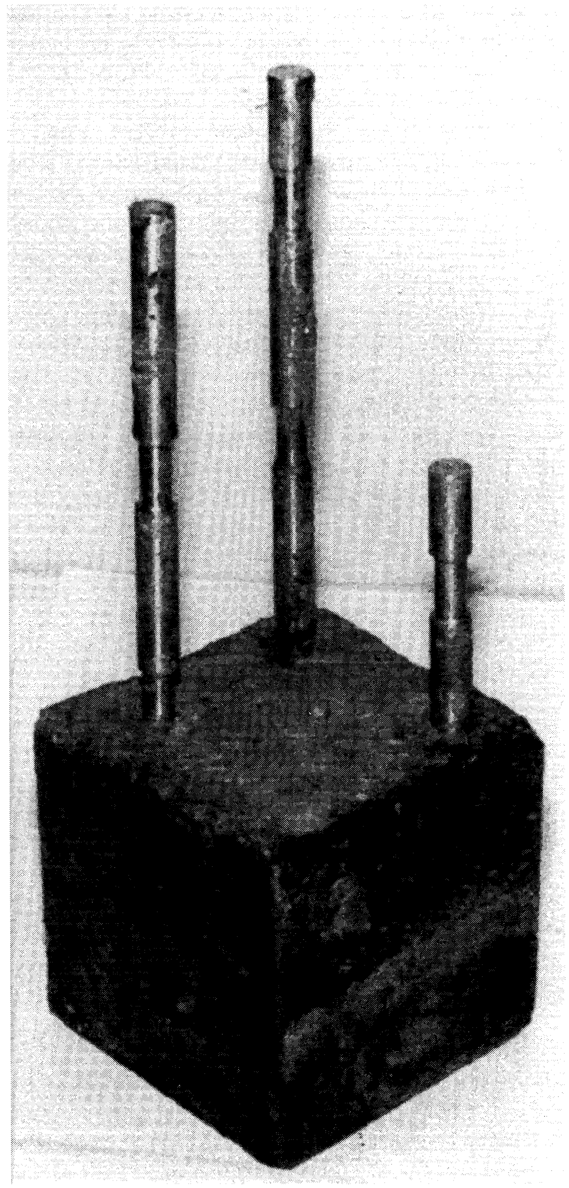

Figure 4: Type 316 stainless steel specimens after removal of upper block of SRPC concrete following $12\frac{1}{2}$ years continuous exposure to seawater and cleaning in running tap water.

Mix 1

Ordinary Portland cement	420 kg/m^3
5 mm Ham River sand	548 kg/m^3
5–10 mm Ham River gravel	275 kg/m^3
10–12·7 mm Ham River gravel	1004 kg/m^3
Water/cement ratio	0·42
Compacting factor	0·80
Cube strength at 28 days	54·3 N/mm^2
	58.3 N/mm^2
	55·3 N/mm^2
mean	55·8 N/mm^2

Mix 2

Sulphate-resisting Portland cement	355 kg/m^3
5 mm Ham River sand	570 kg/m^3
5–10 mm Ham River gravel	285 kg/m^3
10–12·7 mm Ham River gravel	1044 kg/m^3
Water/cement ratio	0·45
Compacting factor	0·85
Cube strength at 28 days	56·2 N/mm^2
	56·7 N/mm^2
	59·6 N/mm^2
mean	57·8 N/mm^2

PREPARATION OF SPECIMENS

The wooden moulds (100 × 100 × 203 mm) were prepared and painted with mould oil. The central wooden diaphragm to form the 3 mm gap between the two cubes and the outside of the steel sleeves through which the steel specimens were to pass, were greased with petroleum jelly. The diaphragm, mould sides, sleeves and steel specimens were assembled. A grc sheet was sprayed, dewatered and demoulded. Pieces to form backing strips were cut before the grc had set and placed on the base of the mould. The assembly of the mould was then completed.

The concrete was then poured into the mould on both sides of the diaphragm, the mould being vibrated continuously to ensure good compaction of the concrete. When the mould was full, the concrete was levelled by trowel. Standard 100 mm cubes were also cast to measure the concrete strength at 28 days. The blocks were left in their moulds for 24 h under moist sacking and polythene sheeting. The steel sleeves around the test specimens were withdrawn after 6 h.

After demoulding, the blocks were immersed in tap water until the day before despatch to the exposure site. They were removed from the water and the surface of the concrete allowed to dry before fixing identification discs. The blind hole above the 150 mm long steel specimen was filled with mortar but leaving a 3 mm diameter hole to prevent any air pockets forming when the specimen was immersed.

EXPOSURE AND EXAMINATION

Two exposure conditions were used: full immersion in Langstone Harbour near Portsmouth on the South Coast of England; and intermittent exposure on a bank in the Harbour subject to tidal immersion. The concrete blocks for full immersion were tied down on wooden trays fixed to steel frames and suspended from rafts in the Harbour at a depth of about 0.6 m. The seawater in the Harbour is fully oxygenated and has an average salinity of about 34 parts per thousand. The water is subject to tidal flow which may reach $3\frac{1}{2}$ knots during spring ebb tides but is less than 1 knot at neap tides. The average water temperature is about 2°C in winter and 18°C in summer. The dual concrete blocks for tidal immersion were tied down on wooden trays fixed to steel frames embedded in the bank. The blocks were out of the water for about 50% of the time.

The SRPC concrete blocks were installed in May 1973 at the raft site and in June 1973 at the tidal site. The OPC concrete blocks were installed some 6 months later in December 1973. The SRPC concrete blocks, exposed to the warmer, summer seawater, were quickly covered with marine fouling but the OPC blocks had an initial period of some 4 months free from fouling.

Blocks were withdrawn from exposure after approximately 1, $3\frac{1}{2}$ and 7 years at each site. Two blocks from the raft site were withdrawn after approximately $12\frac{1}{2}$ years exposure. After removing the concrete the steel specimens were freed from all marine growths by mild brushing in running water and treatment in dilute nitric acid. The extent of any corroded areas was measured by comparison with a 1 mm grid and expressed as a percentage of the surface area of the relevant test region defined in Tables 8 to 15. The depth of attack in individual pits was measured by racking the stage of a calibrated microscope up and down. Where attack was severe, as on the mild steel and on one stainless steel specimen, a micrometer with a point probe was employed to measure pit depth.

The specimens were cut into lengths of 70–120 mm and the tensile strength and elongation of each gauge length measured on a tensile testing machine and compared with the value for the steel determined prior to exposure. A total of 42 stainless steel and 18 mild steel specimens were tested in 20 concrete blocks. The programme is summarized in Table 2.

Experimental results

ONE YEAR EXPOSURE

Exposed surfaces of the concrete blocks and the steel specimens at both sites were entirely covered with marine growth and fouling at the end of the first summer period of exposure.

No corrosive attack on the stainless steel specimens was observed. The mild steel specimens had suffered some corrosion, but this had not affected the tensile strength: a slight effect on elongation was apparent, but this may not have been a real effect, except,

TABLE 2: **Exposure programme.**

Exposure time (years)	Full immersion (raft)			Intermittent immersion (tidal)		
	SRPC		OPC	SRPC		OPC
	Mild steel	Stainless steel	Stainless steel	Mild steel	Stainless steel	Stainless steel
1	Table 3	Table 6	Table 5	Table 4	Table 8	Table 7
$3\frac{1}{2}$	Table 3	Table 6	Table 5	Table 4	Table 8	Table 7
7	Tables 3, 9 Figure 6	Tables 6, 12 Figure 7	Tables 5, 11	Tables 4, 9 Figure 5	Tables 8, 14 Figure 8	Tables 7, 13
$12\frac{1}{2}$		Tables 6, 16 Figures 3, 4, 9	Tables 5, 15 Figure 10			

possibly, for the 250 mm long specimen at the tidal site (Tables 3 and 4).

Characteristic observations made throughout the test series were,

(1) the increasing severity of corrosion with increasing length of specimen, and
(2) more severe corrosion at the tidal site than at the raft site.

THREE AND A HALF YEARS EXPOSURE

Attack on the mild steel had developed further. Corrosion at the 3 mm gap between the blocks had extended slightly into the area of steel embedded in the concrete and this was more pronounced on the longer specimens. Some small patches of corrosion covering 2–5% of the embedded area could be seen. Corrosion of the external areas (i.e. the steel in the flowing seawater) was more severe at the tidal site but the areas embedded in concrete showed similar or slightly less corrosion than those exposed at the raft site. Little effect on tensile strength and elongation was observed (Tables 3 and 4).

Some patches of dull appearance were noted on the stainless steel specimens but there was no other corrosive attack. No effect on strength and elongation was apparent.

SEVEN YEARS EXPOSURE

A more detailed examination was made after exposure for approximately 7 years. The results of visual examination and measurements of the corroded area and depth of attack on the mild steel specimens are given in Tables 9 and 10. Their appearance is shown in Figures 5 and 6. The more severe corrosive attack on the 250 mm specimens is obvious, and so is the overall, more severe corrosion of the specimens at the tidal site. However, a locally intense attack on the 3 mm gap area on the 250 mm specimens at the raft site is evident in Figure 6 and is reflected in the tensile test results (Table 3).

Of all the mild steel specimens tested, this specimen had the greatest area and depth of corrosive attack in the section embedded in concrete.

The stainless steel specimens at the raft site were substantially uncorroded. Descriptions of the type of attack observed and its extent and depth are given in Tables 11 and 12. The appearance of the specimens is shown in Figure 7. There was no measurable effect on tensile strength and ductility (Tables 5 and 6). More severe attack occurred at the tidal site but nevertheless, after removal of rust staining, it was apparent that corrosion was superficial (Figure 8, Tables 13 and 14) and had negligible effect on strength and ductility (Tables 7 and 8).

The results gave an indication that specimens in the SRPC concrete were more liable to suffer corrosion than in the OPC concrete.

TWELVE AND A HALF YEARS EXPOSURE

The appearance of the block made from SRPC concrete immediately after it was removed from the raft is shown in Figure 3. The OPC concrete block was similar. The appearance of the stainless steel specimens after removal from the upper block and cleaning in running water is shown in Figure 4. The specimens from both SRPC and OPC concrete showed rust staining but with one exception had suffered surprisingly little attack after over 12 years immersion in seawater, as is evident from their appearance after brushing and acid treatment (Figures 9 and 10).

Close inspection of Figures 9 and 10 reveals some of the few small areas of generally shallow local corrosion that had occurred.

The most seriously attacked was the 250 mm long specimen in the SRPC concrete block, which suffered severe crevice corrosion starting at its junction with the lower concrete block and progressing downwards into the concrete embedded portion as a result of the acidity developed in the crevice by the corrosion process[4]. Other patches of significant attack also occurred in the same region.

Descriptions of the corrosion and its extent and depth are given in Tables 15 and 16. Apart from the severely corroded specimens, there was no significant effect on the tensile properties (Tables 5 and 6).

The concrete blocks showed no significant deterioration on visual inspection. There was no spalling of the concrete, even in the area of the severely corroded specimen in the SRPC concrete block.

TABLE 3: **Tensile properties of mild steel specimens in SRPC concrete. Continuous exposure at raft site.**

Exposure* (years)	Region† and specimen length (mm)						
	EM	GA		ST			FE
	150	200	250	150	200	250	250
	FRACTURE LOAD (kN) Value before exposure 40·2 kN						
1	41·0	38·0	38·9	41·0	38·3	39·4	39·3
3½	41·4	40·0	38·2	40·8	40·5	39·0	35·5
7	40·7	34·7	29·6	40·5	37·4	36·4	31·1
	ELONGATION (%) Value before exposure 28%						
1	26	24	26	26	26	26	28
3½	24	20	8‡	24	24	22	24
7	30	22	12	30	20	26	32

*Actual exposure periods were: 1 year 42 days; 3 years 298 days; 7 years 63 days.
†EM embedded in concrete
GA 3 mm gap
ST in stagnant seawater in upper block
FE freely exposed to seawater.
‡Fracture outside gauge marks.

TABLE 4: **Tensile properties of mild steel specimens in SRPC concrete. Intermittent exposure at tidal site.**

Exposure* (years)	Region† and specimen length (mm)						
	EM	GA		ST			FE
	150	200	250	150	200	250	250
	FRACTURE LOAD (kN) Value before exposure 40·2 kN						
1	41·6	37·0	38·9	39·0	37·5	38·0	38·3
3½	41·0	36·7	36·6	39·9	36·3	37·0	38·2
7	40·0	40·0	29·4	40·0	37·4	32·0	36·5
	ELONGATION (%) Value before exposure 28%						
1	26	24	20	26	22	30	28
3½	26	20	24	24	24	6‡	24
7	30	24	22	30	26	22	24

*Actual exposure periods were: 1 year 27 days; 3 years 283 days; 7 years 48 days.
‡Fracture outside gauge marks.

TABLE 5: **Tensile properties of Type 316 stainless steel specimens in OPC concrete. Continuous exposure at raft site.**

Exposure* (years)	Region† and specimen length (mm)						
	EM	GA		ST			FE
	150	200	250	150	200	250	250
	FRACTURE LOAD (kN) Value before exposure 40·4 kN						
½	38·9	39·8	39·4	39·0	39·7	39·3	38·9
3½	39·2	40·0	39·9	38·9	40·2	40·0	39·9
6½	36·5	38·3	38·7	38·3	38·7	40·0	39·1
12	40·3	40·0	40·5	40·3	40·0	40·8	40·0
	ELONGATION (%) Value before exposure 81%						
½	70	70	72	72	70	72	72
3½	82	82	82	82	82	82	82
6½	80	84	82	80	82	82	82
12	68	74	70	70	72	70	74

*Actual exposure periods were: 210 days; 3 years 101 days; 6 years 232 days; 12 years 83 days.

TABLE 6: **Tensile properties of Type 316 stainless steel specimens in SRPC concrete. Continuous exposure at raft site.**

Exposure* (years)	Region† and specimen length (mm)						
	EM	GA		ST			FE
	150	200	250	150	200	250	250
	FRACTURE LOAD (kN) Value before exposure 40·4 kN						
1	40·1	40·5	40·2	39·0	40·5	40·2	40·0
3½	38·6	40·2	40·3	38·3	40·4	40·5	40·3
7	39·8	39·1	38·9	39·8	38·2	44·1	44·0
12½	38·0	38·0	39·5	38·5	38·0	40·5	40·0
	ELONGATION (%) Value before exposure 81%						
1	72	70	70	72	70	70	70
3½	80	80	76	80	80	78	78
7	80	82	82	82	82	82	80
12½	72	72	54‡	72	72	70	70

*Actual exposure periods were: 1 year 42 days; 3 years 298 days; 7 years 63 days; 12 years 280 days.
†EM embedded in concrete
GA 3 mm gap
ST in stagnant seawater in upper block
FE freely exposed to seawater.
‡Fractured at gauge mark in corroded area.

TABLE 7: **Tensile properties of Type 316 stainless steel specimens in OPC concrete. Intermittent exposure at tidal site.**

Exposure* (years)	Region† and specimen length (mm)						
	EM	GA		ST			FE
	150	200	250	150	200	250	250
	FRACTURE LOAD (kN) Value before exposure 40·4 kN						
½	39·0	40·2	40·3	39·0	40·0	40·5	40·3
3½	39·2	37·7	40·1	39·1	38·1	40·3	40·2
6½	38·3	38·3	40·0	38·7	37·8	39·6	39·6
	ELONGATION (%) Value before exposure 81%						
½	72	72	70	72	72	70	72
3½	80	82	78	80	78	78	82
6½	82	84	84	84	84	82	80

*Actual exposure periods were: 210 days; 3 years 101 days; 6 years 232 days.

TABLE 8: **Tensile properties of Type 316 stainless steel specimens in SRPC concrete. Intermittent exposure at tidal site.**

Exposure* (years)	Region† and specimen length (mm)						
	EM	GA		ST			FE
	150	200	250	150	200	250	250
	FRACTURE LOAD (kN) Value before exposure 40·4 kN						
1	40·1	40·1	40·2	40·5	40·2	40·4	40·4
3½	40·5	40·5	38·9	40·5	40·5	40·3	40·4
7	38·2	38·3	38·7	38·9	38·5	39·1	39·6
	ELONGATION (%) Value before exposure 81%						
1	70	70	68	72	68	70	72
3½	82	80	82	82	82	82	82
7	84	82	82	82	82	82	84

*Actual exposure periods were: 1 year 27 days; 3 years 283 days; 7 years 48 days.

TABLE 9: **Corrosion of mild steel in SRPC concrete. Continuous immersion at raft site for 7 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	Fairly uniform corrosion with patches of severe attack: deep pitting on upper horizontal surface 100% 1·5 mm	Fairly uniform corrosion: deep pitting on upper horizontal surface 100% 0·6 mm	–
Enclosed within upper block ST	Areas of corrosion increasingly severe towards upper regions 60% 0·35 mm	Fairly uniform corrosion 60% 0·2 mm	A few small areas of rusting: one patch of more severe attack on upper horizontal surface 2% 0·35 mm
3 mm gap GA	Severe corrosion 100% 1·5 mm	Moderately severe corrosion 100% 0·3 mm	Moderately severe corrosion 100% 0·25 mm
Embedded in concrete EM	Areas of rusting increasing near to junction with surface of block. One area of severe attack near junction 13% 1·3 mm	A few small areas of rusting: more severe attack near junction with surface of block 0·5% 0·2 mm	A few small areas of rusting: more severe attack near junction with surface of block 1% 0·2 mm

*Actual exposure period was 7 years 63 days.

TABLE 10: **Corrosion of mild steel in SRPC concrete. Intermittent immersion at tidal site for 7 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	Severe attack especially in region near to concrete block 100% 2·3 mm	Severe, overall attack with areas of deeper penetration 100% 0·8 mm	–
Enclosed within upper block ST	General overall corrosion with patches of severe attack at upper part of region 95% 0·85 mm	Extensive patches of corrosion 20% 0·4 mm	Patches of local corrosion 3–4% 0·4 mm
3 mm gap GA	Severe corrosion 100% 0·65 mm	Moderately severe corrosion 60% 0·3 mm	Sharply defined area of corrosion extending into upper area 100% 0·3 mm
Embedded in concrete EM	Local rusting with severe attack near junction with surface of block 10% 0·65 mm	Severe attack near junction with surface of block 7% 0·6 mm	A few small areas of corrosion near junction with surface of block 3–4% 0·15 mm

*Actual exposure period was 7 years 48 days.

TABLE 11: **Corrosion of stainless steel in OPC concrete. Continuous immersion at raft site for 7 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	No corrosion Nil Nil	Slight local etching Nil Nil	–
Enclosed within upper block ST	Few small areas of local corrosion 0·1% 0·03 mm	No corrosion Nil Nil	Slight local etching Nil Nil
3 mm gap GA	Slight local etching Nil Nil	No corrosion Nil Nil	Very slight local etching Nil Nil
Embedded in concrete EM	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil

*Actual exposure period was 6 years 232 days.

TABLE 12: **Corrosion of stainless steel in SRPC concrete. Continuous immersion at raft site for 7 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	One small area of local corrosion 0·2% 0·21 mm	Very slight local etching Nil Nil	–
Enclosed within upper block ST	Very slight local etching: one small pit 0·03% 0·09 mm	Very slight local etching Nil Nil	Very slight local etching Nil Nil
3 mm gap GA	Very slight local etching Nil Nil	No corrosion Nil Nil	Very slight local etching Nil Nil
Embedded in concrete EM	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil

*Actual exposure period was 7 years 63 days.

TABLE 13: **Corrosion of stainless steel in OPC concrete. Intermittent immersion at tidal site for 7 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	Several small patches of local corrosion 0·7% 0·2 mm	Numerous areas of local corrosion and pitting 3·6% 0·6 mm	–
Enclosed within upper block ST	Isolated slight local corrosion 0·15% 0·03 mm	One area of shallow local corrosion 0·15% 0·03 mm	Slight local etching Nil Nil
3 mm gap GA	Very slight local etching Nil Nil	No corrosion Nil Nil	Very slight local etching Nil Nil
Embedded in concrete EM	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil

*Actual exposure period was 6 years 232 days.

TABLE 14: **Corrosion of stainless steel in SRPC concrete. Intermittent immersion at tidal site for 7 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	Numerous small areas of shallow corrosion 1·8% 0·32 mm†	Several small areas of shallow corrosion 1% 0·15 mm	–
Enclosed within upper block ST	A few small areas of shallow corrosion 0·1% 0·06 mm	Several small areas of shallow corrosion 0·3% 0·04 mm	No corrosion Nil Nil
3 mm gap GA	No corrosion Nil Nil	No corrosion Nil Nil	No corrosion Nil Nil
Embedded in concrete FM	One area of shallow corrosion just below 3 mm gap 0·03% 0·03 mm	Slight dulling of surface Nil Nil	Slight dulling of surface Nil Nil

*Actual period of exposure was 7 years 48 days.
†More severe pitting present at neck of gauge length was not measurable.

TABLE 15: **Corrosion of stainless steel in OPC concrete. Continuous immersion at raft site for 12 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	Slight local etching Nil Nil	One small area of shallow attack 2% 0·03 mm	–
Enclosed within upper block ST	Slight, local etching Nil Nil	Slight local etching Nil Nil	Slight local etching Nil Nil
3 mm gap GA	Slight local etching Nil Nil	One small area of local corrosion 1% 0·05 mm	Slight local etching Nil Nil
Embedded in concrete EM	Slight dulling of surface Nil Nil	Some local etching: one local area of corrosion with pitting 0·2% 0·2 mm	Slight dulling of surface Nil Nil

*Actual period of exposure was 12 years 83 days.

TABLE 16: **Corrosion of stainless steel in SRPC concrete. Continuous immersion at raft site for 12 years*.**

Region	Description, area (%), and depth (mm) of corrosion		
	250 mm specimen	200 mm specimen	150 mm specimen
Outside upper block FE	One small area of local corrosion 0·1% 0·05 mm	One small area of attack associated with barnacle 0·3% 0·15 mm	–
Enclosed within upper block ST	Several areas of local corrosion in lower part of region 1% 0·32 mm	A few small areas of shallow corrosion 0·3% 0·22 mm	No corrosion Nil Nil
3 mm gap GA	Some very small areas of local corrosion 2·5% 0·12 mm	No corrosion Nil Nil	No corrosion Nil Nil
Embedded in concrete EM	Extensive, deep localized corrosion commencing at junction with surface of block: other patches of local corrosion 5% 3·56 mm	Dulling of surface Nil Nil	Slight dulling of surface Nil Nil

*Actual period of exposure was 12 years 280 days.

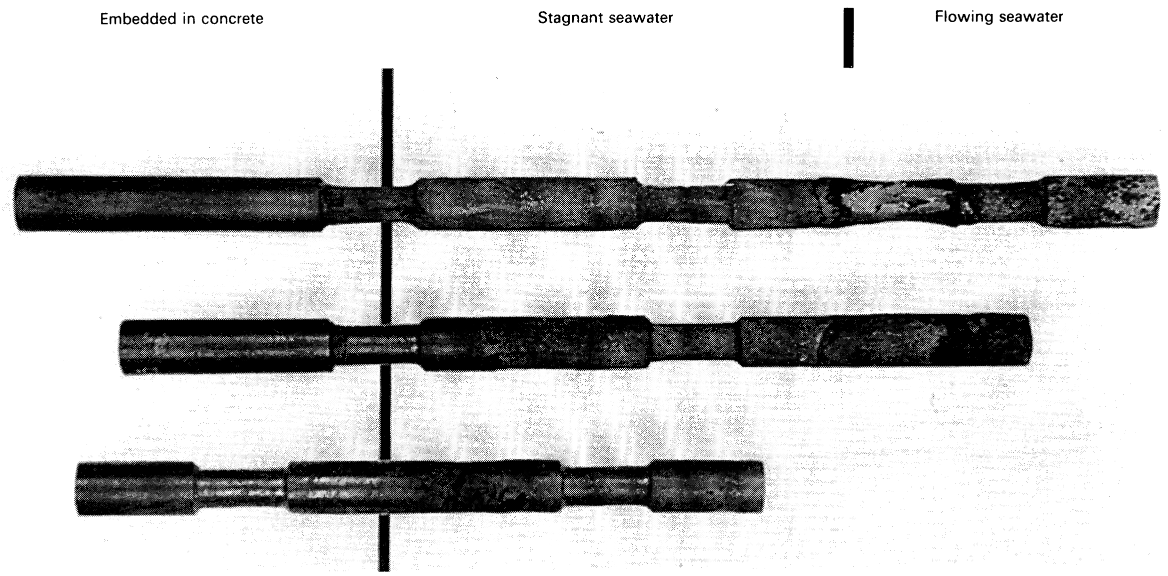

Figure 5: Mild steel specimens from SRPC concrete, 7 years intermittent immersion at tidal site, after mild cleaning.

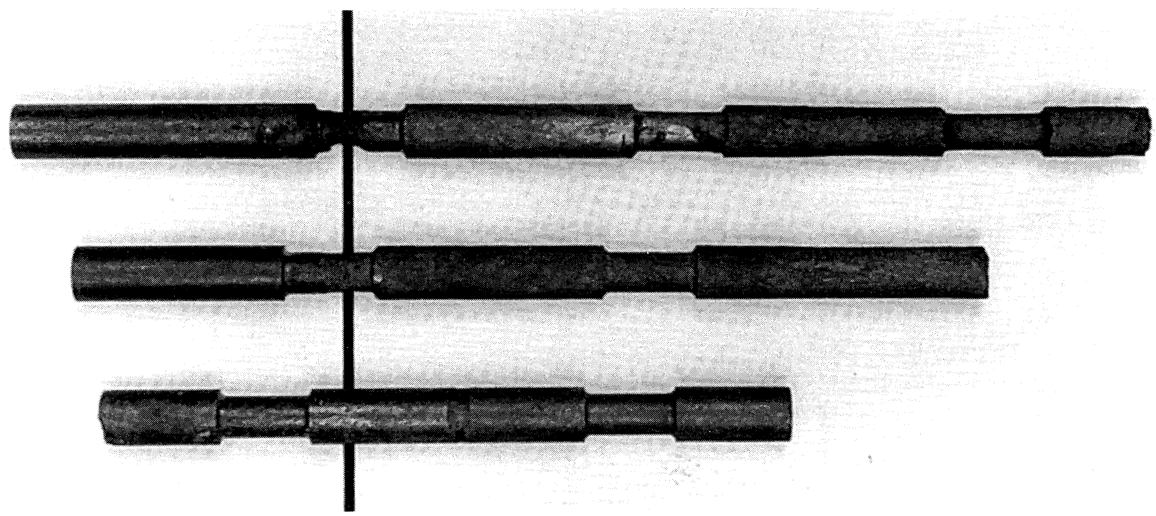

Figure 6: Mild steel specimens from SRPC concrete, 7 years continuous immersion at raft site, after mild cleaning.

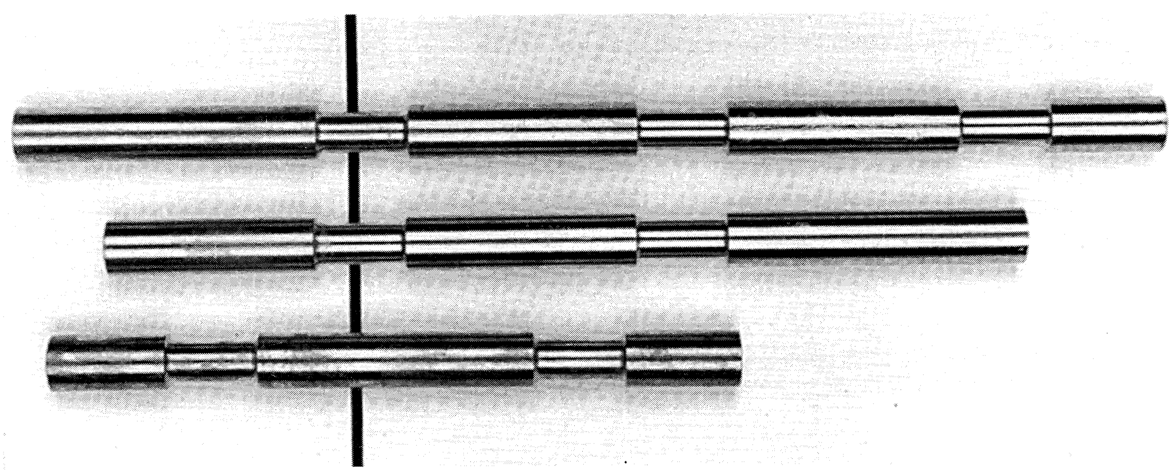

Figure 7: Stainless steel specimens from SRPC concrete, 7 years continuous immersion at raft site, after mild cleaning.

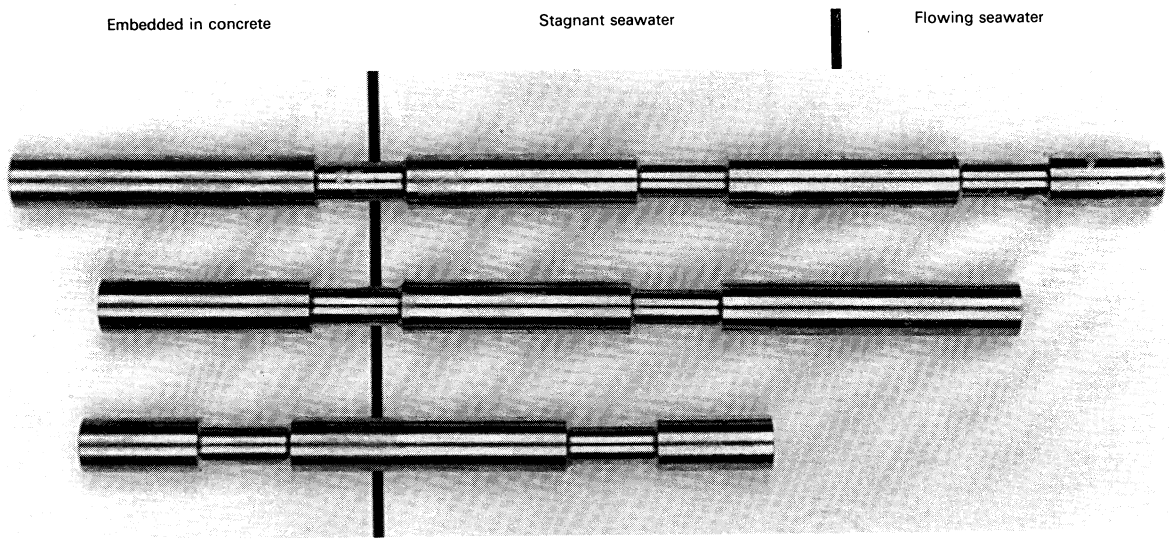

Figure 8: Stainless steel specimens from SRPC concrete, 7 years intermittent immersion at tidal site, after mild cleaning.

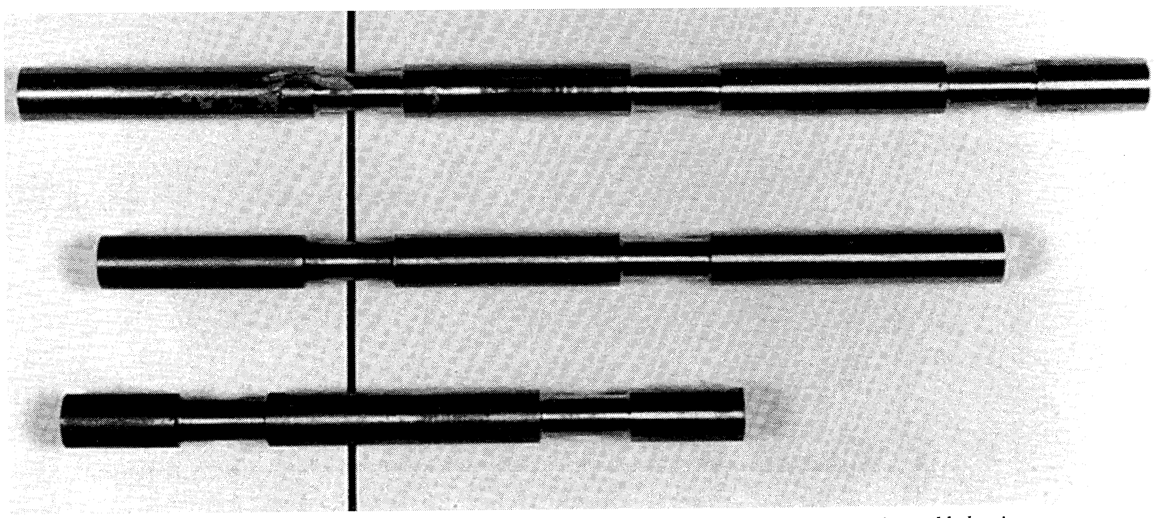

Figure 9: Stainless steel specimens from SRPC concrete, $12\frac{1}{2}$ years continuous immersion at raft site, after mild cleaning.

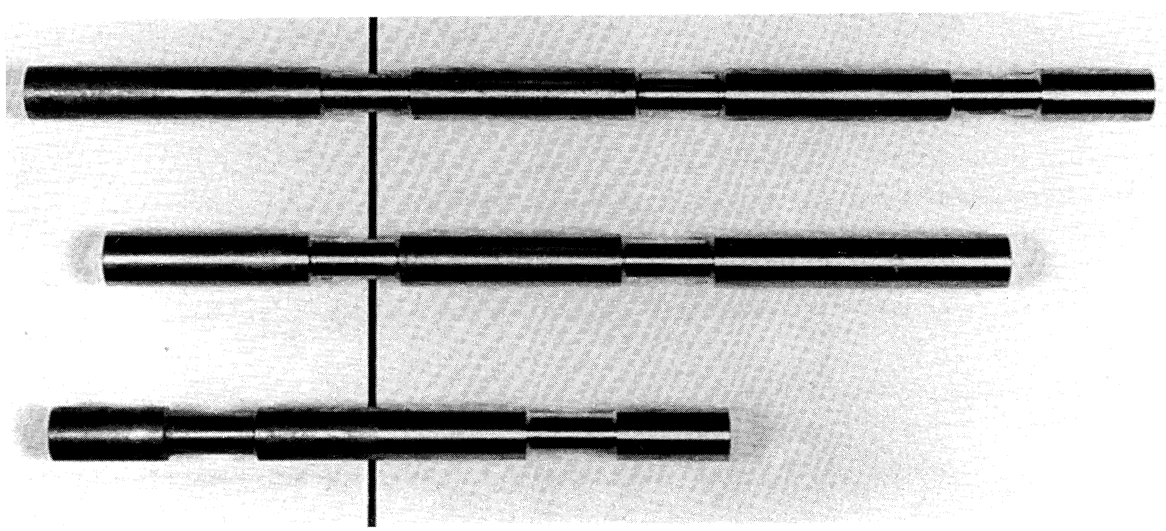

Figure 10: Stainless steel specimens from OPC concrete, $12\frac{1}{2}$ years continuous immersion at raft site, after mild cleaning.

Discussion

Corrosive attack on the mild steel specimens was substantial. The concrete provided good protection except for the region near to the interface with seawater where severe attack was apparent in all but one specimen. Despite the substantial corrosive attack, the effect on tensile strength and elongation was of significance only on the longest specimens (250 mm) that had undergone 7 years exposure.

In contrast, the surprising feature of the tests was the small extent of corrosion of the Type 316 stainless steel, even after as long a period as $12\frac{1}{2}$ years immersion in seawater.

The literature abounds with references to the susceptibility of stainless steel, even the molybdenum bearing grades, to localized corrosion in chloride-containing waters[5–8], which in adverse circumstances of narrow, deep crevices and large external surface area can take place rapidly[4,9]. To a slight extent the small size of the specimens contributed to the unexpectedly small degree of corrosion observed, but it is considered that the major factor was the beneficial influence of the concrete.

EFFECT OF CONCRETE ON THE POTENTIAL OF STAINLESS STEEL

The pH of the electrolyte contained within the pores of concrete is known to be within the range 13–14 in the early stages after curing and may be expected to fall to about 12·6 after a period of exposure to seawater[10]. Alkali concentrations of this magnitude would lower the potential of stainless steel to a value much less noble than those in seawater, i.e. to a value below that at which pitting corrosion could occur[11,12].

In the present tests, depression of potential would also extend to the stainless steel surface outside the concrete. Clearly the effect would be less, the greater the external area of stainless steel, and this is, therefore, one reason for the greater susceptibility of the longest steel specimens to corrosion. Additionally, the adverse influence of a large external cathodic area in increasing the propagation of localized corrosion is well-known[5,9].

At the tidal site, the low potential of stainless steel embedded within the concrete would be unable to influence the externally exposed areas of stainless steel to any significant extent during the period of atmospheric exposure. This is a further reason for the greater attack at the tidal site. Two other factors are the effects of the greater degree of oxygenation of cathodic areas and the increased concentration of chloride caused by evaporation of the seawater during the atmospheric exposure period.

The beneficial effect of the concrete in providing a protective environment to stainless steel only partly embedded in it is of practical importance in situations such as dowels between slabs, fixings for precast units or for plant.

CEMENT TYPE

The effect of the two different types of cement, OPC and SRPC, on the corrosion of stainless steel specimens can be clearly distinguished. OPC has a higher proportion of tricalcium aluminate (C_3A) than SRPC—typically 12% compared with 3%. Indeed, the proportion of C_3A permitted in SRPC is limited to 3.5% by BS4027[13].

The beneficial effect of C_3A in complexing choride ions and so delaying their migration into concrete exposed to chloride solutions has been commented upon by numerous authors[10,14,15].

In the present series of tests, the OPC concrete at the raft site gave greater protection to the stainless steel—to both embedded and external areas—than did the SRPC concrete. It is reasonable to assume that the greater reserve of alkalinity and the slower penetration of chloride ions as a result of the higher cement content of the OPC concrete delayed a rise of potential of the stainless steel to values at which localized corrosion could occur.

At the tidal site, the extent of corrosion of stainless steel in the two types of concrete did not differ significantly, suggesting that the greater corrosion of the external areas at this site occurred mostly during exposure to the atmosphere.

It is known that sulphate in seawater can react with C_3A, reducing concrete strength and causing expansion[16]. Thus, the desirability of having a high C_3A content to limit chloride ingress has to be qualified by the requirement for a low C_3A content to minimize susceptibility to sulphate attack. Long-term exposure tests and observations on structures made with different cements have generally shown that sulphate attack does not occur with cements with C_3A contents below about 8%[17].

On the other hand, Verbeck[18] found that reinforced concretes made with SRPC cements with C_3A contents between 2 and 5% were five times as vulnerable to cracking due to the steel rusting as cements with 8–11% C_3A. Lea and Watkins[19] showed in tests up to 10 years that an unusually rich mix (cement : aggregate $1:2\frac{3}{5}$) was beneficial in preventing deterioration of reinforced concrete piles in seawater.

It would appear that insofar as stainless steel fixtures in concrete are concerned, the C_3A content of the cement should not be less than 8%.

For concrete structures required to be resistant to de-icing salts and other chloride environments of low sulphate content, it is clearly desirable to have the lowest possible aggregate/cement and water/cement ratios compatible with cost and other factors in order to obtain the greatest reserve of alkalinity and maximum C_3A content and thus protection of reinforcing steel and fixtures.

CREVICE CORROSION

The severe corrosion that occurred on one stainless steel specimen after $12\frac{1}{2}$ years immersion in seawater was initiated:

(1) at the most susceptible point, i.e. at the position of the tightest crevice—the stainless steel/seawater/concrete junction;
(2) on the specimen having the greatest outside (cathodic) area; and
(3) in the concrete having the lowest proportion of cement, i.e. the lowest reserve of alkalinity and the lowest C_3A content.

It is possible that, with a mass of concrete larger than the 100 mm cube in the present tests, there would have been sufficient reserve of alkalinity and sufficient diffusion of hydroxyl ions, even with SRPC concrete, to have inhibited attack. Despite the extensive corrosive attack near the interface there was no evidence of spalling or cracking of the concrete in the adjacent region.

The failure of this one specimen permits identification of those factors favouring long life and successful application of stainless steel fixtures in concrete structures used in chloride environments.

Conclusions and recommendations

(1) Type 316 stainless steel, partly embedded in concrete and exposed to seawater showed excellent corrosion resistance, significantly better than would be expected from the well-recorded experience of the behaviour of the steel in chloride environments. It is considered that the alkalinity of the concrete exerted a beneficial effect, even to areas remote from the embedded section.

(2) Where the area of stainless steel outside the concrete was small, corrosive attack was non-existent or superficial, even after more than 12 years immersion.

(3) Where the area of stainless steel extending outside OPC concrete was larger (i.e. on 250 mm long specimens with 72 mm in flowing seawater), some local corrosion occurred but this was insufficient to affect strength or ductility.

(4) The crevice corrosion that was expected to occur quite rapidly on stainless steel partly embedded in concrete exposed to seawater was observed on only one specimen and only after more than 12 years exposure.

(5) It is considered that the following recommendations will minimize, if not completely eliminate, the slight susceptibility to crevice corrosion shown by Type 316 stainless steel partly embedded in concrete when exposed to solutions containing chlorides:

(a) Concrete with the lowest aggregate/cement and water/cement ratios should be used in order to provide a dense concrete with a substantial reserve of alkalinity and the maximum permissible content of C_3A to reduce the effect of chlorides. Account may need to be taken of the conflicting requirement for resistance to sulphate attack of a restriction in the content of C_3A.

(b) The area of stainless steel external to the concrete should be reduced to a minimum, and also the area of electrochemically noble materials such as bronzes and cupro-nickels in electrical contact with it. This can be done effectively by painting the external area of stainless steel or electrochemically noble material. The same beneficial effect can be achieved by contacting the stainless steel with electrochemically base materials such as mild steel, zinc or aluminium.

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REFERENCES

1. SOCIETY OF CHEMICAL INDUSTRY. *Proceedings of Symposium on corrosion of steel reinforcements in concrete construction.* London, 1979.
2. BUILDING RESEARCH ESTABLISHMENT. Digest No. 263. *The durability of steel in concrete: Part 1.* Garston, 1982. 8pp.
3. HAYNES, J. M. Stainless steel reinforcement. *Civil Engineering.* August 1984 pp. 23, 27–28.
4. OLDFIELD, J. W. Crevice corrosion of stainless steels–the importance of crevice geometry and alloy composition. *Metaux Corrosion-Industrie.* No. 668, 1981. pp. 134–47.
5. LAQUE, F. L. *Marine corrosion.* J. Wiley & Sons, 1975. pp. 116–117.
6. ALEXANDER, A. L., SOUTHWELL, C. R. and FORGESON, B. W. Corrosion of metals in tropical environments–Part 5, Stainless steel. *Corrosion.* Vol. 17, 1961. pp. 345t–352t.
7. FLINT, G. N. Resistance of stainless steels to corrosion in naturally occurring waters. *Corrosion y Proteccion.* Vol. 8, 1977. pp. 23–34.
8. SEDRIKS, A. J. *Corrosion of stainless steels.* New York, Wiley Interscience, 1979. pp. 63–88.
9. OLDFIELD, J. W., LEE, T. S. and KAIN, R. M. Avoiding crevice corrosion of stainless steels. *Proceedings of conference–Stainless Steel—'84.* London, The Institute of Metals, 1985. pp. 205–216.
10. PAGE, C. L. and TREADAWAY, K. W. J. Aspects of the electrochemistry of steel in concrete. *Nature.* Vol. 297, 1982. pp. 109–114.
11. LECKIE, H. P. and UHLIG, H. H. Environmental factors affecting the critical potential for pitting in 18–8 stainless steel.

Journal of the Electrochemical Society. Vol. 113, No. 12, 1966. pp. 1262–7.

12. LECKIE, H. P. A contribution to the applicability of critical pitting potential. *Journal of the Electrochemical Society*. Vol. 117, No. 9, 1970. pp. 1152–4.
13. BRITISH STANDARDS INSTITUTION. BS4027: 1980. *Specification for sulphate-resisting Portland cement*.
14. MIDGELY, H. G. and ILLSTON, J. M. The penetration of chlorides into hardened cement pastes. *Cement and Concrete Research*. Vol. 12, 1984. pp. 546–58.
15. CALLEJA, J. Durability. *Proceedings of 7th International Congress on the Chemistry of Cement, Paris, 1980*. Editions Septima, 1980. Vol. 7, pp. 2/1–2/48.
16. LEA, F. M. and DESCH, C. H. *The chemistry of cement and concrete*. London, Edward Arnold, 1976.
17. BROWNE, R. D. The performance of concrete structures in the marine environment. *Corrosion in the marine environment*, London, 1973. Institution of Marine Engineers, 1974. pp. 80–7.
18. VERBECK, G. J. Field and laboratory studies of the sulphate resistance of concrete. *Performance of concrete*. Editor: E. G. Swenson. University of Toronto, Canadian Building Series, 1968. pp. 113–24.
19. LEA, F. M. and WATKINS, C. M. *The durability of reinforced concrete in sea water*. HMSO, 1960. National Building Studies Research Paper No. 30.