EFFECT OF CRACKS ON THE CORROSION OF EMBEDDED STEEL IN SILICA-CONCRETE COMPARED TO ORDINARY CONCRETE

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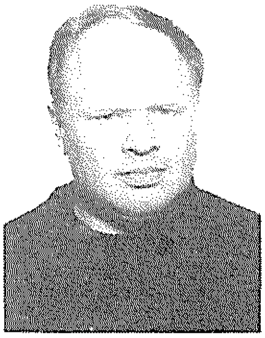

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ABSTRACT

Laboratory experiments have been made to study the effect of introduced cracks on the corrosion of the reinforcing steel bars. The concrete specimens were made of both ordinary Portland Cement and ordinary Portland Cement with 10% Silica Fume as a cement substitute.
The compressive strength of the concrete varied from about 30 MPa to about 85 MPa. After hydration the specimens were exposed to a chloride containing environment and the corrosion rate and the corrosion potential of the embedded steels exposed in the cracks were recorded. The effect of crack width and the effect of silica fume on the corrosion of embedded steel are discussed.

Key words: Silica-concrete, cracks, corrosion

1. INTRODUCTION

Steel embedded in concrete is normally protected against corrosion by the chemical properties of the pore water in the concrete. If, however, cracks are introduced into the concrete harmful species might penetrate to the steel surface and destroy the protective effect of the concrete. In air the loss of protection is usually caused by carbonation and in sea water or other marine environment the loss of protection is caused by chloride ions as illustrated in figure 1.

For cracks occurring in concrete structures experiences indicate that a healing of the cracks may take place due to the precipitation of reaction products between constituents of the sea water and the pore solution of the concrete. Corrosion products may also clog the crack at an early stage of the corrosion process.

In order to study the effect of cracks on the corrosion of embedded steel a number of laboratory experiments has been carried out. The testing procedure was about the same as earlier reported [1]. Crack width and concrete compo-

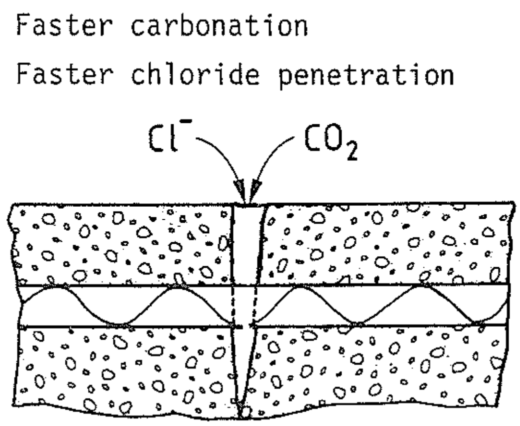

Figure 1.
Influence of concrete cracks.

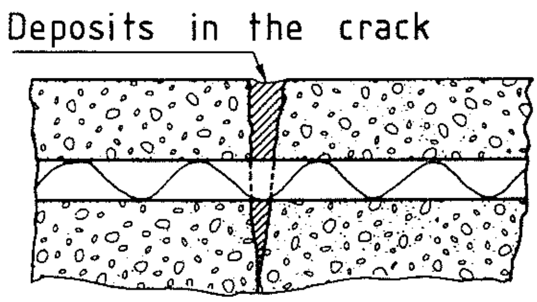

Figure 2.
Self-healing of concrete cracks.

sition were laboratory testing variables. The concrete were made from ordinary Portland Cement and ordinary Portland Cement with Silica Fume as cement substitute.

It should be noted that the experimental condition applied does not necessarily coincide with field conditions. For a concrete structure which is completely submerged in sea water the condition will be quite different. But for structures partly exposed to other environments the oxygen supply in certain areas, for example in splash or tidal zones, might be of the same high order as in these experiments. Also on bridge decks the availability of oxygen will be high enough to support corrosion in cracks.

2. EXPERIMENTAL

2.1 Materials

Typical analyses of ordinary Portland Cement and Silica Fume used are given in tables 1 and 2 respectively.

Table 1.
Typical analyses of Standard Portland Cement (8.6% C_3A).

COMPOUND	WEIGHT PER CENT
SiO_2	20.60
Fe_2O_3	2.68
Al_2O_3	4.97
CaO	65.12
MgO	1.50
SO_3	2.62

Table 2.
Typical analyses of Silica Fume.

COMPOUND	WEIGHT PER CENT
SiO_2(balance)	94.7
Tot. C	0.40
Tot. S	0.10
Fe	0.36
Al	0.09
Ca	0.44
Mg	0.63
K	0.89
Na	0.15

2.2 Test specimens

The test specimens were made from five different concrete qualities (table 3), in three of these mixtures silica fume was used as cement substitute. The amount of silica fume used correspond to 10% of cement weight. The physical properties of the concretes are listed in table 4.

Table 3. Concrete composition.

COMPONENTS	MIX PROPORTION BY WEIGHT				
	C25/00	C25/10	C55/00	C55/10	C85/10
Portland Cement	1.00	1.00	1.00	1.00	1.00
Silica Fume	-	0.10	-	0.10	0.10
Water	0.77	1.09	0.45	0.58	0.41
Sand	4.33	5.78	2.46	2.35	2.15
Filler	0.33	0.44	0.14	0.14	0.12
Crushed stone	3.81	5.14	2.63	2.52	2.30

Table 4. Concrete properties.

PHYSICAL PARAMETER	MEASURED VALUE OF PHYSICAL PARAMETER				
	C25/00	C25/10	C55/00	C55/10	C85/10
Slump (cm)	9.5	15	16	10.5	14.4
Density of mixture (kg/m^3)	-	2420	2540	2460	2460
Density of hardened concrete (kg/m^3)	2540	2490	2570	2490	2590
Compressive strength 7 days (MPa)	27.7	16.7	48.6	43.8	60.0
Compressive strength 28 days (MPa)	32.2	29.4	55.4	58.6	81.8

Totally 60 prisms (10 x 10 x 60 cm), 12 of each concrete quality were made. A 50 cm rod of Ø 10 mm reinforcing steel was placed in the center of each prism. Electrical connection for measuring purposes was made by a rubber insulated metal wire attached to the steel rod. By means of rubber insulating it was ensured that only as received steel surface (mill scaled) was exposed to the concrete.

After casting the test specimens were water cured at room temperature 3 months. On each specimen a single crack was introduced by three point loading.

After cracking the load was applied until a given crack opening was observed. The crack width of the specimens - measured on the concrete surface - varied from 0.1 to 1.4 mm.

The prisms were partly covered by tape so that only the crack showing at the front side of the specimen was exposed.

2.3 Testing procedure

All specimens were submerged in sea water at room temperature. The reinforcing steels were electrically connected to separate 10 x 60 cm sheets of stainless steel. By this arrangement the exposed steel within the crack will act anodic (corrode). The steel sheet is cathode and supplies the "driving force" of the corrosion process. The cathodic part of the corrosion process is therefore separated from the anodic process. It is therefore possible to monitor the corrosion rate of the reinforcing steel exposed in the crack.

In this experimental set up the stainless steel sheet simulates a large non corroding rebar steel network in a submerged concrete structure. Since the oxygen rate of diffusion into the steel surface has been shown to be about 100 times higher in stagnant sea water than in concrete [2], the steel sheet will correspond to about 10 m^2 of rebar steel surface.

The experiment continued for 38 weeks with weekly measurements of galvanic current flowing between embedded steel and the corresponding steel sheet.

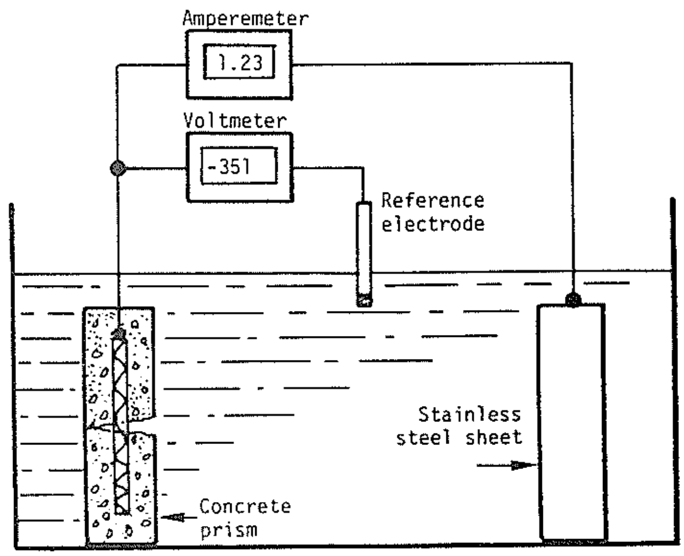

Figure 3. Experimental set-up.

The recorded current value is a direct measure of the corrosion of the steel exposed in the concrete crack. The rate of corrosion can be visualized in different terms, but the degree of the corrosion attack is highly dependent upon the surface area of corroded steel exposed.

3. RESULTS AND DISCUSSION

In table 5 are listed the mean corrosion current and the calculated weight loss of steel after 38 weeks of exposure. The samples on which corrosion were observed during the experimental period show four different patterns:

Table 5.1. Mean corrosion current and calculated weight loss of quality C25 specimens.

Concrete type	Crack width (mm)	Start of corrosion after weeks	End of corrosion after weeks	Mean current (μA)	Calculated weight loss (g)
Ordinary Portland Cement	0.1	-	-	0.6	< 0.01
	0.1	-	-	0.9	0.01
	0.15	-	-	1.0	0.01
	0.2	-	-	0.6	< 0.01
	0.3	-	-	0.6	< 0.01
	0.4	33	→	14	0.09
	0.5	36	→	4.2	0.03
	0.6	11	→	150	1.0
	0.6	11	→	140	0.9
	0.8	2	→	230	1.6
	0.8	-	-	.8	0.01
	0.9	7	→	245	1.6
Ordinary Portland Cement and silica fume 10 % of cement weight	0.1	-	-	2.2	0.02
	0.2	-	-	1.7	0.01
	0.25	-	-	1.8	0.01
	0.25	1	2	5.8	0.04
	0.35	-	-	1.4	0.01
	0.4	-	-	1.4	0.01
	0.5	2	→	140	0.9
	0.55	2	→	120	0.8
	0.7	7	36	63	0.4
	0.85	1	→	180	1.2
	0.85	1	→	170	1.1
	1.1	1	→	180	1.2

1. Immediate start of corrosion. After some time the corrosion rate reduces to zero (figure 4).
2. Immediate start of corrosion. The corrosion rate is on a high level during the experiment (figure 5).
3. Initiation period occur before start of corrosion. After some time the corrosion rate reduced again to zero (figure 6).
4. Initiation period occur before start of corrosion. The corrosion rate is on a high level during the rest of the experiment (figure 7).

Table 5.2. Mean corrosion current and calculated weight loss of quality C55 specimens.

Concrete type	Crack width (mm)	Start of corrosion after weeks	End of corrosion after weeks	Mean current (µA)	Calculated weight loss (g)
Ordinary Portland Cement	0.1	-	-	0.6	< 0.01
	0.15	-	-	0.6	< 0.01
	0.2	1	3	0.6	< 0.01
	0.2	1	→	95	0.6
	0.35	-	-	0.7	≅ 0.01
	0.4	4	7	1.7	0.01
	0.4	-	-	0.5	< 0.01
	0.7	-	-	0.6	< 0.01
	0.7	8	→	100	0.7
	0.9	6	→	140	0.9
	0.9	12	27	67	0.4
	0.9	8	→	100	0.7
Ordinary Portland Cement and silica fume 10 % of cement weight	0.1	1	→	100	0.7
	0.1	-	-	0.8	0.01
	0.25	-	-	1.0	0.01
	0.4	-	-	0.9	0.01
	0.4	4	→	64	0.4
	0.5	-	-	0.8	0.01
	0.6	1	27	50	0.3
	0.7	1	→	110	0.8
	0.7	-	-	0.6	0.01
	0.8	3	→	100	0.7
	0.9	1	→	170	1.1
	1.0	1	→	120	0.8

The results indicate that when reinforced concrete containing silica fum are susceptible to rebar corrosion in cracks the corrosion process start more rapidly than in concrete with no silica fume. This test shows that of 22 specimens with silica in which corrosion was observed the process started during the first two weeks of exposure on 17 of the specimens. The corresponding numbers for concrete without silica were 13 and 3 respectively. During the experimental period selfhealing was observed on 7 of the specimens. This effect seems not to be dependent upon concrete type or quality.

On figure 8-10 are presented plots of weight loss vs crack width. There seems to be no distinct difference between weight loss and crack width a specimens without silica fume (figure 8) and specimens with silica fume (figure 9). The corresponding plot of all specimens is shown in figure

According to figure 10 few specimens with crack width less than 0.4 mm h been attacked by harmful corrosion and specimens having crack width more than 0.6 mm are quite susceptible to corrosion attack.

Table 5.3. Mean corrosion current and calculated weight loss of quality C85 specimens.

Concrete type	Crack width (mm)	Start of corrosion after weeks	End of corrosion after weeks	Mean current (μA)	Calculated weight loss (g)
Ordinary Portland Cement and silica fume 10 % of cement weight	0.1	-	-	0.7	≅ 0.01
	0.15	-	-	0.6	< 0.01
	0.3	-	-	0.7	≅ 0.01
	0.4	19	21	1.2	0.01
	0.55	2	→	90	0.6
	0.6	-	-	0.7	≅ 0.01
	0.6	1	→	110	0.7
	0.7	1	→	100	0.7
	0.8	1	→	120	0.8
	0.8	1	→	125	0.8
	1.0	1	→	240	1.6
	1.4	1	→	180	1.2

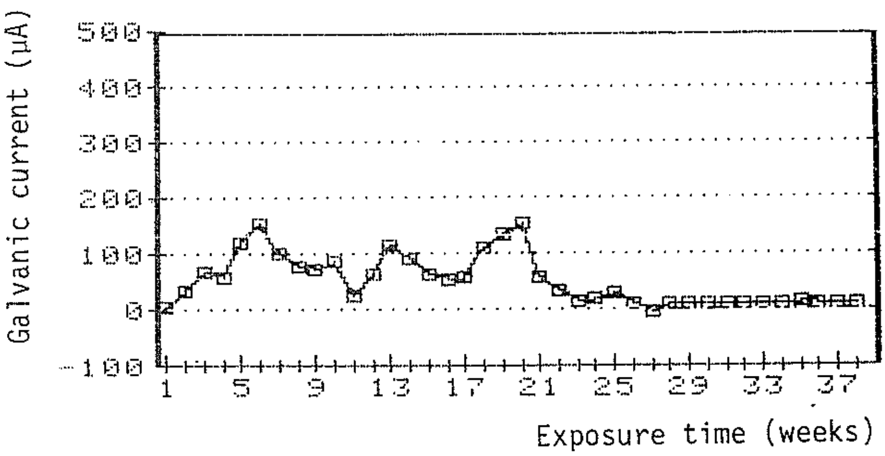

Figure 4. Galvanic current vs time for a typical catetory 1 specimen. After an immediate start the corrosion process tends to zero. Concrete: C55 with 10% silica fume. Crack width: 0.6 mm.

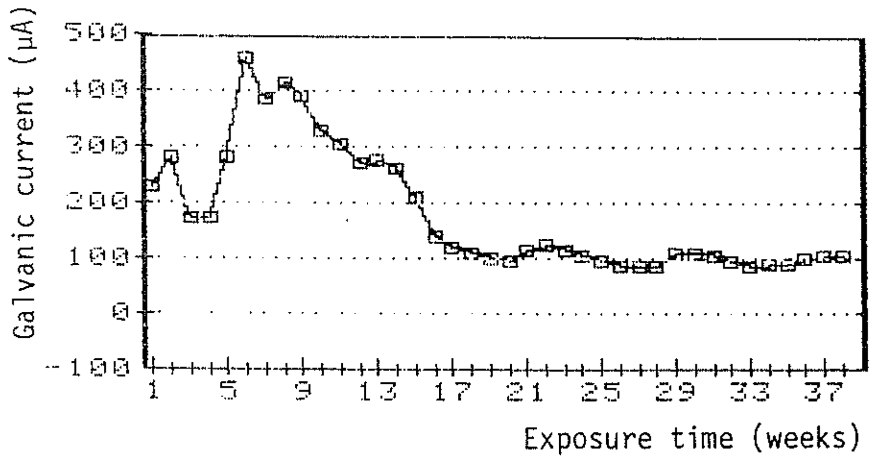

Figure 5. Galvanic current vs time for a typical category 2 specimen. The corrosion process starts immediately and continues. Concrete: C85 with 10% silica fume. Crack width: 1.4 mm.

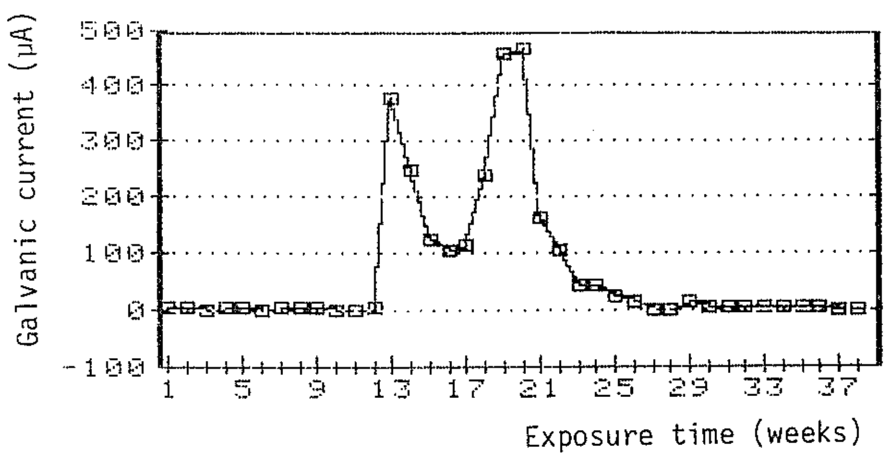

Figure 6. Galvanic current vs time for a typical category 3 specimen. After an initiation period the corrosion starts and thereafter tends to zero. Concrete C55 with no silica fume. Crack width: 0.9 mm.

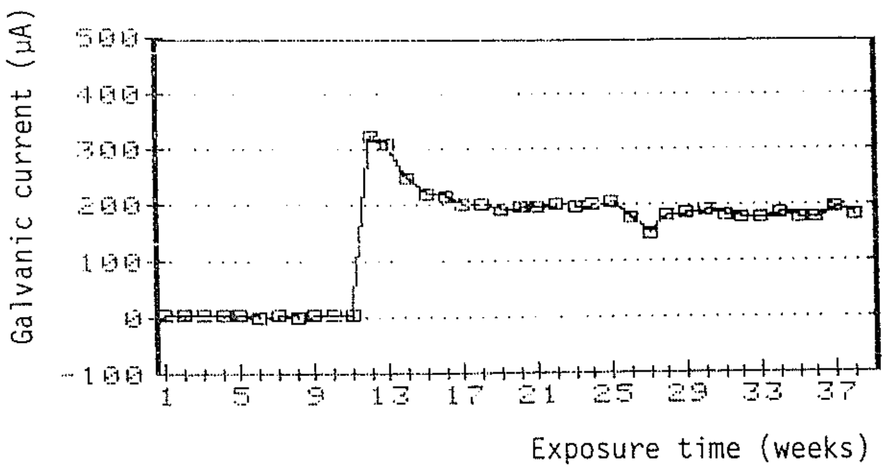

Figure 7. Galvanic current vs time for a typical category 4 specimen. After an initial period the corrosion starts and continues. Concrete: C25 with no silica fume. Crack width: 0.6 mm.

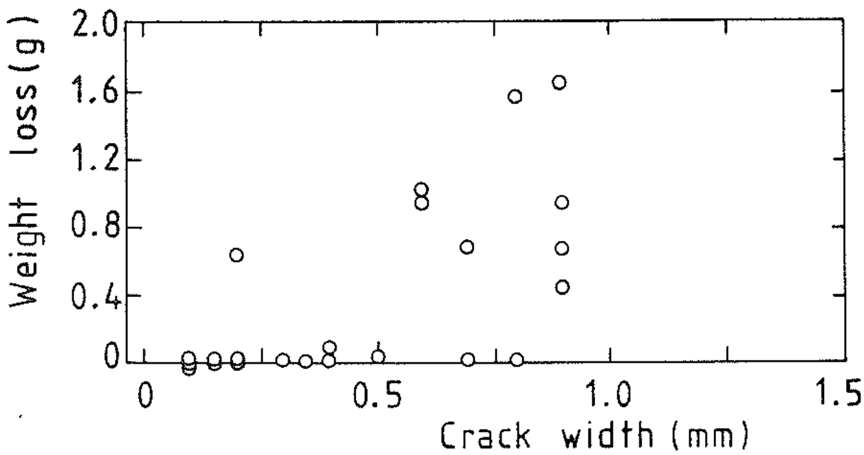

Figure 8. Weight loss vs crack width, specimens without silica fume.

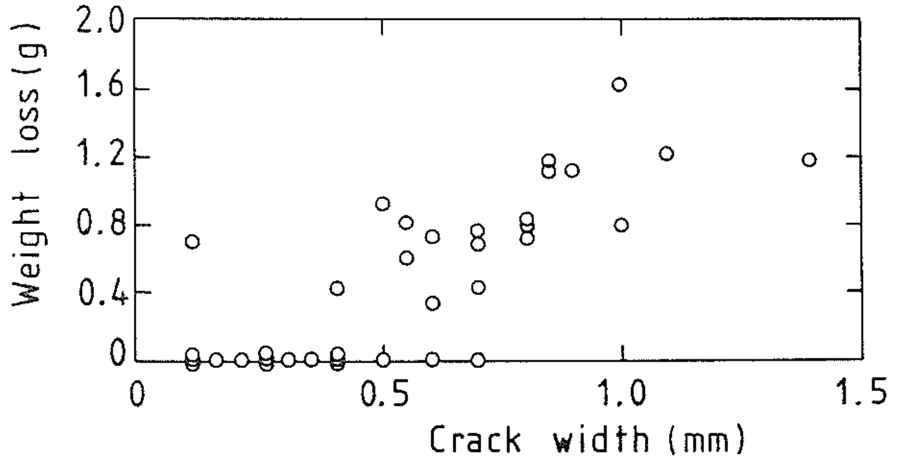

Figure 9. Weight loss vs crack width, specimens with 10% silica fume.

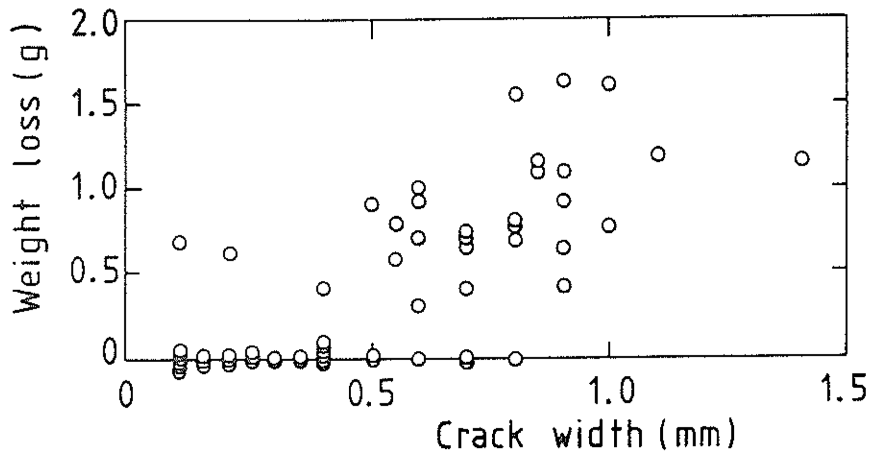

Figure 10. Weight loss vs crack width, all specimens.

In figure 11 the distribution of corroded specimens according to three groups of crack widths has been plotted. The criteria of corrosion used is calculated weight loss of at least 0.1 g during the experimental period. That means that specimens where corrosion was initiated at a late stage are classified as not corroding.

The figure demonstrates that there is no effect of silica fume with respect to corrosion due to cracks. It also demonstrates the relation between crack width and corrosion as earlier reported [1]. It should be noted, however, that the specimens have not been inspected. It is possible that at the end of the exposure period, the inspection might show that for the specimens with crack widths below 0.4 mm the galvanic currents measured are due to leakage along the lead. This have also been earlier reported [1].

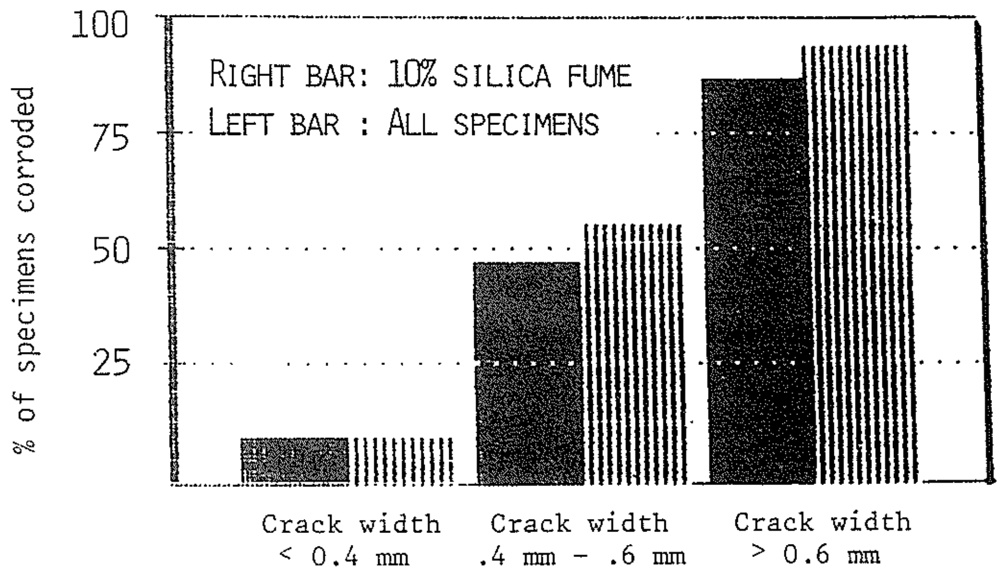

Figure 11. Distribution of corroded specimens according to crack width.

4. SUMMARY

The experiments carried out indicate that for a submerged concrete structure there is no distinct difference between the risk of corrosion of rebar steel in cracks in concrete with silica fume compared to concrete without silica fume. For crack widths lower than 0.4 mm the risk of corrosion is very small and for crack widths higher than 0.6 mm the risk is high with the conditions used for this experiment.

But it must be emphasized that in these experiments the availability of oxygen was very high. In field conditions this parameter is an important controlling factor of the corrosion process and is dependent upon a number of factors, of which the humidity of the concrete is most important.

5. REFERENCES

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