

Wolfseher und Partner AG

Beratende Materialtechnologen und Bauingenieure

Sika AG, Zurich

FerroGard-903 Corrosion Inhibitor
Material Technology Test

Baar, 6 March 1997, Report No. 96.144.11

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Summary

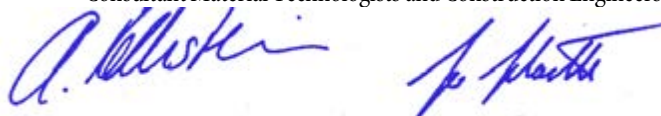
Sika AG has developed a new type of active corrosion inhibitor, Sika FerroGard. The product forms a protective film on the surface of the steel reinforcement which retards the start of corrosion and reduces the corrosion rate. The new inhibitor has been fully checked by Sika AG in laboratory test, the application and long-term behaviour of the product, has now been investigated by Wolfseher und Partner AG in a test programme under realistic conditions. The investigations on concrete surfaces without additional protective coating applied show the following:

- . FerroGard 903 can be detected analytically when applied on concrete surfaces after crushing of the cores taken, extraction and analysis of the nitrogen content.
- . The protective film thickness on the steel necessary for effective corrosion protection by FerroGard 903 is extremely low. This means that the required concentration in relation to the concrete weight calculated from this is also low, which makes the use of FerroGard 903 extremely effective.
- . The effect of the carbonation level, capillary porosity and water saturation level on the penetration capacity of FerroGard 903, assessed by later analyses of the FerroGard 903 concentration as a factor of the depth, is insignificant.
- . FerroGard 903 was detected down to a depth of 50 mm on specimens subjected to accelerated weathering simulating natural weathering of ten years in Zurich, Switzerland. The corrosion protection effect of FerroGard 903 is therefore preserved. It was also shown in [4] that the protective film already adhering to the steel is extremely resistant to weathering (leaching).
- . The risk of incipient anode formation can be ruled out.

Given proper compliance with the safety and application instructions and a quality assurance concept as indicated in the report, the use of Sika FerroGard-903 is a technically simple, effective and durable method of repairing reinforce concrete structures.

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1 Starting point

Sika AG has developed a new type of active corrosion inhibitor, Sika FerroGard. The product can be used either as a concrete additive for fresh concrete (Sika FerroGard-901) or as a repair material (Sika FerroGard-903).

This aminoalcohol and inorganic inhibitor blended product promotes the formation on the surface of the steel reinforcement of a protective film (similar to a passive layer) which retards the start of corrosion and reduces the corrosion rate. Sika FerroGard provides both anodic and cathodic corrosion protection: The protective inhibitor film both inhibits ferrous decomposition (anodic reaction) and restricts oxygen access to the steel surface (cathodic reaction).

The new corrosion inhibitor has been fully tested by Sika AG in the laboratory. Its penetration capacity was examined by mass spectrometry. Its action on chlorides was detected by X-ray photoelectron spectroscopy. The corrosion protection effect was acceptably proven both by electrochemical measurements in solution and on realistic test specimens. Sika AG provided Wolfseher und Partner AG with comprehensive literature on the laboratory tests carried out.

Despite the basic evidence of the corrosion protection effect of FerroGard, there was little knowledge of the application and long-term behaviour of the product. This is now investigated in a test programme under realistic conditions and as a field testing product for the repair of structures.

2 Order

Sika AG placed an order with Wolfseher und Partner AG to provide practical functional verification for later application of Sika FerroGard corrosion inhibitor in a realistic test programme. All the investigations referred to below relate to the product FerroGard 903.

3 Basis

- . Meeting between Messrs. Dietrich, Sager and Schümperli (Sika AG) and Schädler and Dr. Wolfseher (Wolfseher und Partner AG) on 12 June 1996.
- . Meeting between Messrs. Dietrich, Dr. Mäder and Schümperli (Sika AG) and Flüeler, Schädler and Dr. Wolfseher (Wolfseher und Partner AG) on 3 July 1996.
- . Sika AG brochure and technical data sheets on the FerroGard product [1].
- . Article "A new class of corrosion inhibitors for reinforced concrete" by U. Mäder, Sika AG [2].
- . Test report "Evaluation of Sika FerroGard", Mott MacDonald, Ref. 26,063/001 Rev. A, April 1996 [3].
- . Test report "Sika FerroGard 901 and 903 Corrosion Inhibitors: Evaluation of Test Programme", Mott MacDonald, Ref. 26,063/001 Rev. B, August 1996 [4].

4 Tests

4.1 Application tests

To investigate the penetration capacity of FerroGard-903 into concrete under various realistic conditions, 20 concrete slabs measuring 400x400x50 mm were made. The cement content (CEM I 42.5) of all the slabs was 300 kg/m³. The following influences on the penetration capacity were examined (Figs 1 and 3):

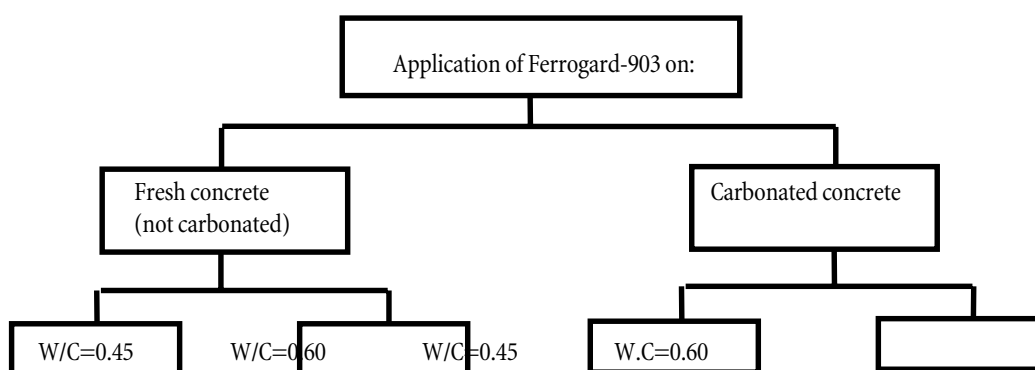


Fig 1: Effect of the carbonation level and W/C ratio of the concrete on the penetration capacity.

Carbonation level

To investigate the effect of the carbonation level in the concrete on the penetration capacity of FerroGard, some of the concrete test slabs were subjected to accelerated carbonation before application. The carbonation depth varied from 0 (fresh concrete) to about 45 mm (almost complete carbonation by acceleration).

The specimens were stored for 28 days in a sealed test chamber and exposed to an atmosphere rich in carbon dioxide (Fig 2 and Photo 1 of the photographic records).

The natural carbon dioxide concentration in the air is approximately 0.03%vol.%, while the atmosphere in the above test chamber had a carbon dioxide concentration of about 10 vol.%. Assuming that the carbonation rate is directly proportional to the concentration, a high or almost complete carbonation level is reached during the 28-day accelerated carbonation process. The carbonation depths were measured by phenolphthalein indicator and are listed in Table 1.

Sealed chamber

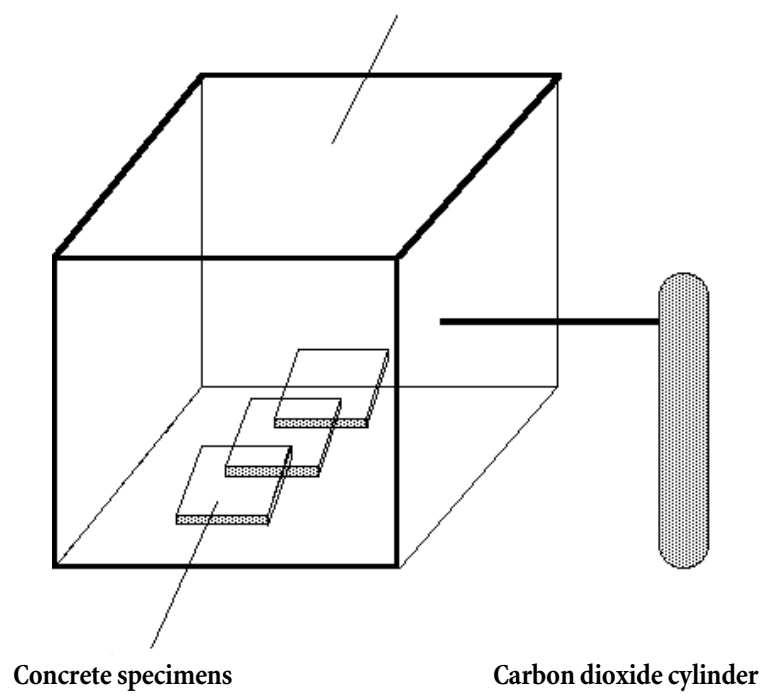


Fig 2: Accelerated carbonation of test slabs in a carbon dioxide rich atmosphere.

Water/cement ratios

Samples with a water/cement ratio of 0.45 or 0.60 were produced. Their capillary porosity is shown in Table 1.

Water saturation levels

The water saturation level of the capillary pores in undried specimens was around 30 vol.%. Specimens dried for two days at 50°C had water saturation levels of around 5 vol.%.

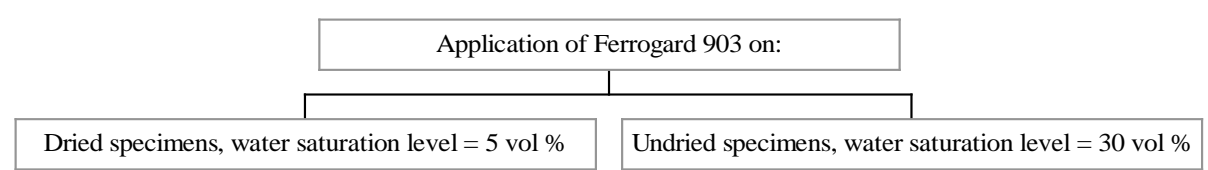


Fig 3: Influence of the water saturation level of the concrete.

Table 1 lists the W/C ratio, capillary porosity, carbonation depth, water saturation level during application and quantity of FerroGard-903 applied per square metre for each specimen. The untreated specimens were used for the tests in Section 4.5.

Sample No.	W/C ratio	Capillary porosity [vol.%]	Carbonation depth [mm]	Water saturation level on application [vol.%]	FerroGard consumption [g/m ²]
1	0.45	9.9	0	30	550
2	0.45	10.2	0	31	580
3	0.45	10.3	0	29	530
4	0.45	10.5	45	28	530
5	0.45	10.9	47	30	530
6	0.60	15.5	0	30	630
7	0.60	14.5	45	31	600
8	0.45	13.7	0	5	575
9	0.60	13.3	46	28	620
10	0.60	13.9	0	29	590
11	0.60	13.1	0	31	-
12	0.60	14.0	0	29	-
13	0.60	13.5	0	30	-
14	0.60	13.2	0	27	-
15	0.60	13.5	0	5	575
16	0.45	10.1	47	7	420
17	0.45	10.5	0	28	-
18	0.45	10.3	0	30	550
19	0.45	10.9	0	-	-
20	0.60	11.6	45	4	440

Table 1: Details of the concrete test slabs.

The FerroGard 903 solution supplied by Sika AG was applied to the concrete slabs in the quantities listed above in ten operations. The FerroGard 903 consumption rate was deliberately slightly higher than the figure of 400-500 g/m² given in the Sika AG Technical Data Sheet [1]. The material was applied at a temperature of 23°C and humidity of 50% RH using a low-pressure hand spray. A period of 15 minutes was left between the various operations until the concrete surface had dried to a slightly damp state.

4.2 Penetration depth after application

Specimen preparation

The specimens used for analysis of the FerroGard 903 content in the concrete were prepared as follows:

- . Cores taken from the concrete slabs with a water-cooled core drill.
- . Cores cut into approx. 12 mm slices with a water-cooled stone blade (Fig 4).
- . Slices crushed with a cooled jaw crusher.
- . Fine grinding with an enclosed ball mill.

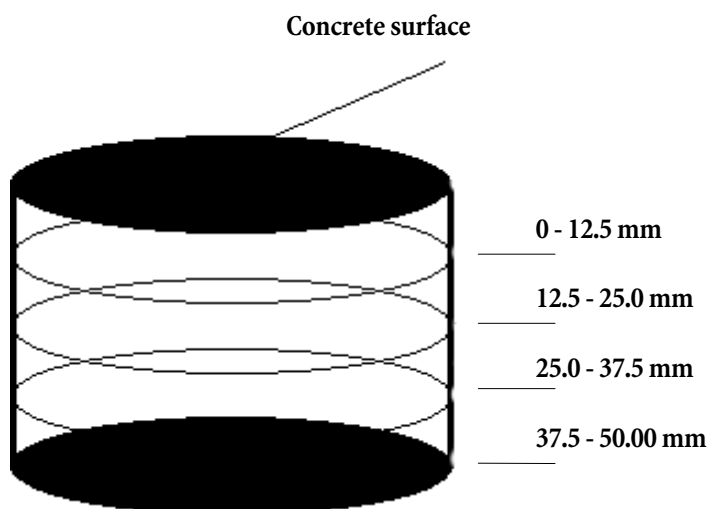


Fig 4: Cores cut into slices

The specimen preparation described above ensured that a temperature of 50°C was not exceeded and specimen crushing took place in a sealed system. This ensured that the inhibitor in the specimens did not evaporate and falsify the analysis results.

Analysis

The FerroGard concentration in the concrete was analysed more than 28 days after application. The effect described in [4] of FerroGard concentration levelling in the concrete during the period between 3 and 28 days after application due to FerroGard penetration in the gas phase was not investigated, since the concentration after a period of more than 28 days after application is more relevant to practical use on site.

The FerroGard concentration was analysed by means of the nitrogen content of the concrete, by the following sequence:

- . 10 g core dust was mixed with pure water and extracted for two hours in a vibrating machine.
- . In one part of the specimen, the nitrate nitrogen was analysed photometrically by EDI method 35 (salicylate method), to determine the nitrogen content in the concrete before FerroGard application.
- . In another part of the extract, the nitrogen component of the aminoalcohol was broken down with Oxisolv (Merck product No. 1.12936) and the nitrate nitrogen content was again analysed by photometry.
- . After deduction of the nitrate nitrogen content, the nitrogen component concentration was used to convert to μg FerroGard per gram of concrete.
- . The detection limit for the above analysis method is $\leq 0.1 \mu\text{g}$ nitrogen per gram of concrete (= $0.9 \mu\text{g}$ FerroGard per gram of concrete).

The calculation of the FerroGard concentration from the nitrogen concentration was based on the following figures:

Density:	1.13 g/cm ³
Dry substance:	31.1 wt.%
N content of liquid FerroGard:	3.5%
N content of dry substance:	11.2%

Test results

Listed in Table 2 are the FerroGard concentrations found to a depth of 50 mm after application on undried specimens with a W/C ratio of 0.45 or 0.60 and on almost fully carbonated and virtually uncarbonated specimens.

Listed in Table 3 are the FerroGard concentrations found to a depth of 50 mm after application on dried and undried specimens.

Sample No.	Depth [mm]	Nitrogen content [μg concrete]	FerroGard content [μg /g concrete]	Carbonation [mm]	W/C
16	0 - 12.5	23	205.4	47	0.45
	12.5 - 25.0	0.8	7.1		
	25.0 - 37.5	0.3	2.7		
	37.5 - 50.0	0.1	0.9		
18	0 - 12.5	25	223.2	≈ 0	0.45
	12.5 - 25.0	0.7	6.3		
	25.0 - 37.5	0.1	0.9		
	37.5 - 50.0	0.1	0.9		
7	0 - 12.5	22	196.4	45	0.60
	12.5 - 25.0	0.8	7.1		
	25.0 - 37.5	1.0	8.9		
	37.5 - 50.0	1.1	9.8		
10	0 - 12.5	21	187.5	≈ 0	0.60
	12.5 - 25.0	1.1	9.8		
	25.0 - 37.5	0.9	8.0		
	37.5 - 50.0	0.6	5.4		

Table 2: FerroGard content two months after application (influence of W/C ratio and carbonation level).

Fig 5 shows the influence of the water/cement ratio and therefore the capillary porosity on the penetration capacity. Fig 6 shows the influence of the carbonation level on penetration. Fig 7 compares the penetration capacity of FerroGard in dried and undried concrete.

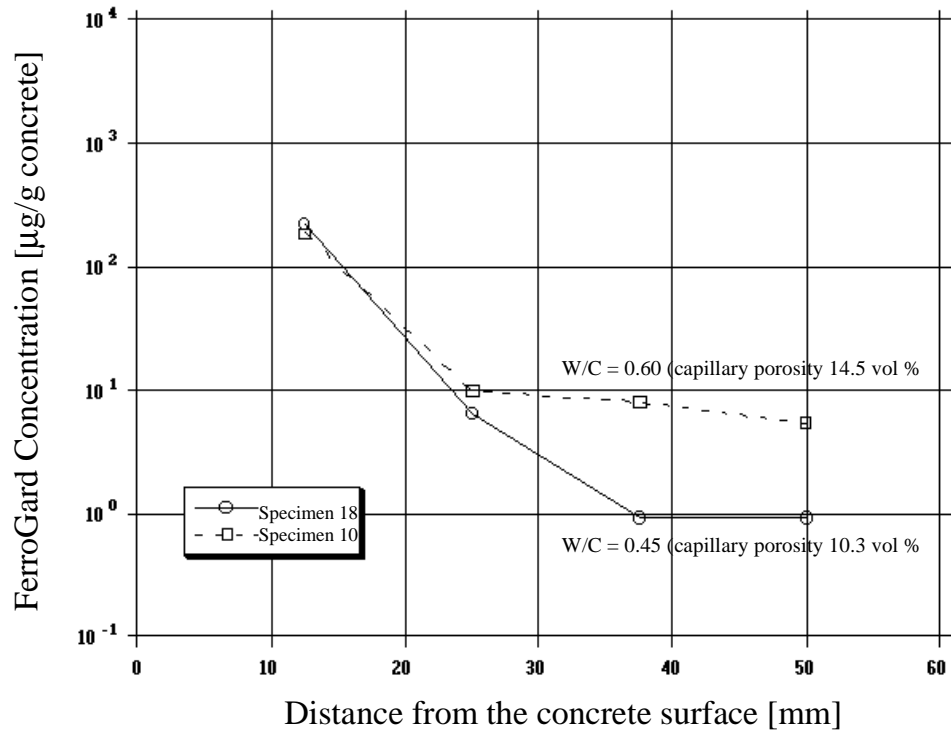


Fig 5: Influence of the W/C ratio on the FerroGard penetration depth. The carbonation depth in both specimens is practically 0 mm.

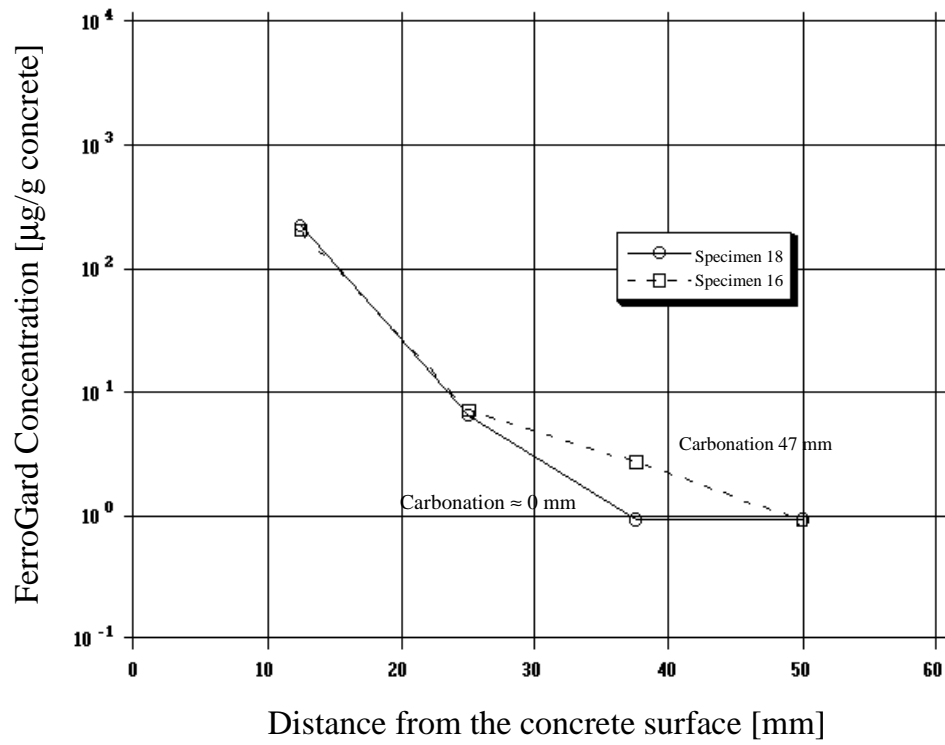


Fig 6: Influence of the carbonation level on the penetration capacity of FerroGard. The water/cement ratio of both specimens was 0.45.

Sample No.	Depth [mm]	Nitrogen content [μg concrete]	FerroGard content [μg /g concrete]	Water saturation level [vol.%]	Drying before application
8	0 - 12.5	21	187.5	5	50°C
	12.5 - 25.0	6	53.6		
	25.0 - 37.5	3	26.8		
	37.5 - 50.0	0.1	0.9		
15	0 - 12.5	21	187.5	5	50°C
	12.5 - 25.0	20	178.6		
	25.0 - 37.5	7	62.5		
	37.5 - 50.0	0.1	0.9		
18	0 - 12.5	25	223.2	30	
	12.5 - 25.0	0.7	6.3		
	25.0 - 37.5	0.1	0.9		
	37.5 - 50.0	0.1	0.9		
10	0 - 12.5	21	187.5	29	
	12.5 - 25.0	1.1	9.8		
	25.0 - 37.5	0.9	8.0		
	37.5 - 50.0	0.6	5.4		

Table 3: FerroGard content more than 28 days after application (influence of water saturation level of capillary pores).

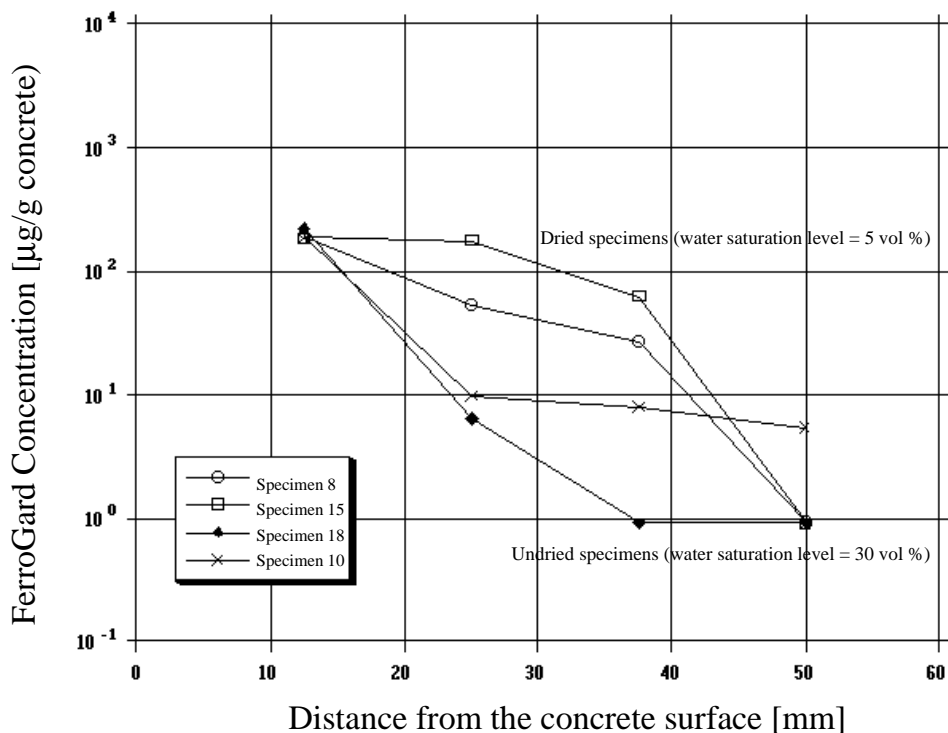


Fig 7: Comparison of the depth profiles of the specimens dried for two days at 50°C before FerroGard application (water saturation level \approx 5 vol.%) with those of undried specimens (water saturation level \approx 30 vol.%).

Summary of results

- . In all the specimens tested, FerroGard 903 was detected in a concentration $\geq 0.9 \mu\text{g}$ per gram of concrete down to a depth of 50 mm.
- . The FerroGard 903 concentration of the specimens with higher porosity (higher W/C ratio) tends to be higher at the same distance from the surface.
- . The influence of the carbonation level on the penetration capacity is negligible.
- . Penetration improves slightly to a depth of about 40 mm if the specimens are dried before application.

4.3 Calculation of the theoretical concentration limit of FerroGard in the concrete

To ensure effective corrosion protection by applying FerroGard, the thickness of the passive layer on the steel consisting of aminoalcohol and associated radicals must be a minimum of 10^{-8} m (10 nm) [4]. Under a quality assurance system, it is advisable to calculate from this the FerroGard concentration limit which must be present behind the first layer of reinforcement.

A model calculation is carried out below to estimate the FerroGard concentration in μg per gram of concrete which must be present for formation of the corrosion protection film. It is assumed that the protective film is formed only by the aminoalcohol corrosion inhibitor.

A concrete area of one square metre and a reinforcement layer with twelve bars (\varnothing 10 mm) is considered (Fig 8). The weight of the 10^{-8} m thick protective film is then calculated.

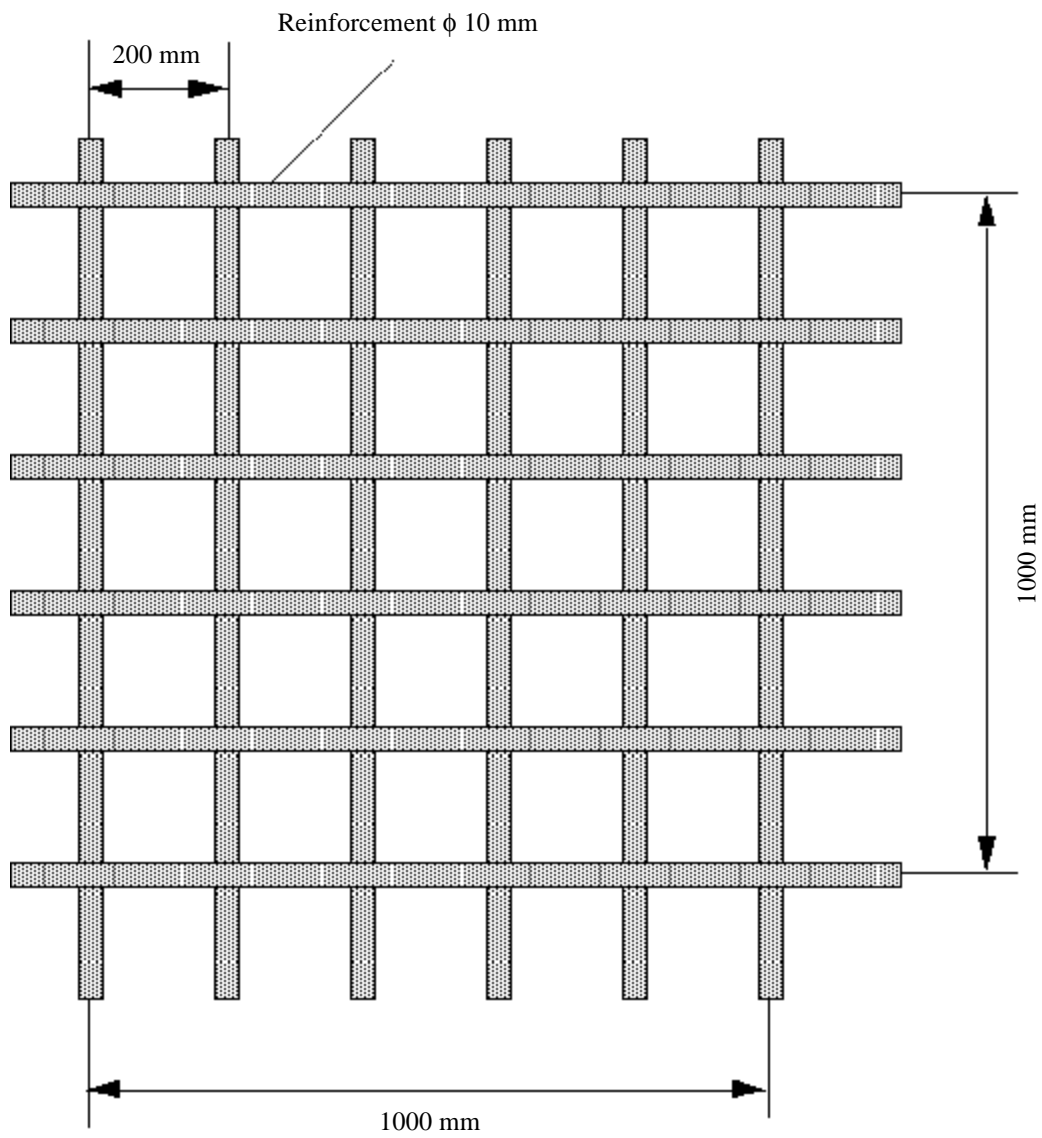


Fig 8: Calculation of the steel surface of the first reinforcement layer. The calculation uses 12 reinforcing bars of $\phi 10$ mm per square metre.

Protective film thickness: 10^{-8} m

Protective film volume: $V = 12\pi h (r_1^2 - r_2^2) = 3.8 \cdot 10^{-9} \text{ m}^3$ $r_1: 5 \cdot 10^{-3} + 10^{-8}$ m
 $r_2: 5 \cdot 10^{-3}$ m

FerroGard density: $1,130 \text{ kg/m}^3$

Protective film weight: $4.3 \cdot 10^{-3} \text{ g} = 4.3 \text{ mg}$ FerroGard per m^2 of concrete
 (dry substance)

The reinforcement layer has a total thickness of 20 mm (Fig 9). To calculate the FerroGard concentration in the concrete from the protective film weight calculated above, the weight of a concrete slab measuring $1000 \times 1000 \times 20$ mm less the reinforcement layer must be calculated (Figs 9 and 10).

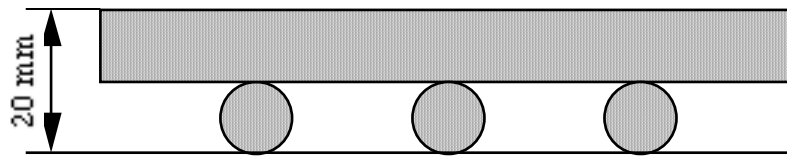


Fig 9: Thickness of reinforcement layer

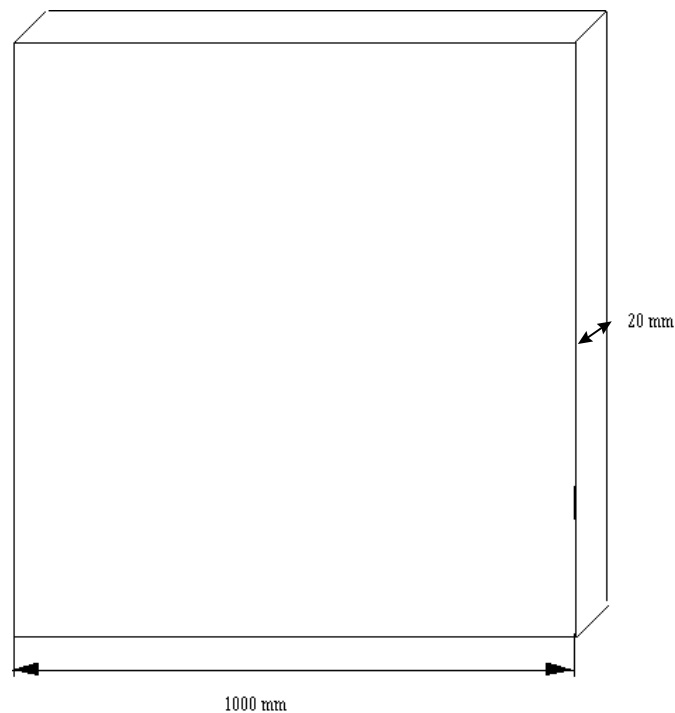


Fig 10: Concrete slab model

Concrete slab volume excluding reinforcing steel volume:

$$V = V_{\text{concrete slab}} - V_{\text{reinforcing steel}} = lbh - 12 \Pi h(r)^2 = 0.0191 \text{ m}^3$$

Concrete slab weight: $0.019 \cdot 2,300 = 43.8 \text{ kg}$
(assumed density of concrete = 2300 kg/m^3)

FerroGard concentration to form the protective film: $4.3 \text{ mg} / 43,832 \text{ g}$

$\approx 0.1 \mu\text{g}$ FerroGard 903 per gram of concrete

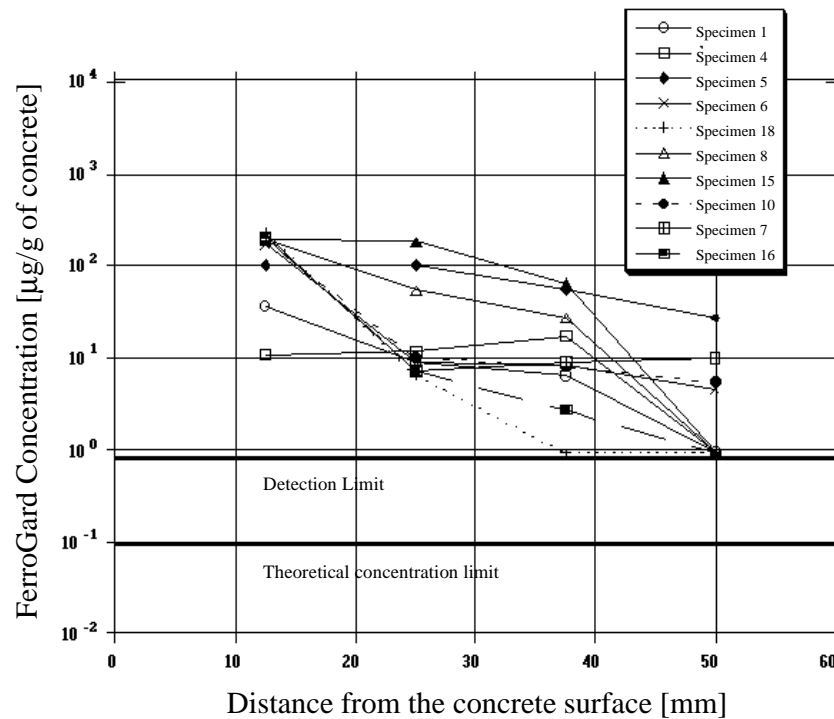


Fig 11: Depth profiles after ten applications of FerroGard solution on test slabs with a capillary porosity of 10 or 12 vol.% (W/C ratio 0.45 or 0.60) with and without leaching.

Discussion

Fig 11 shows the FerroGard concentration as a factor of the distance from the concrete surface for all the specimens analysed and the theoretical concentration limit for the effectiveness of the FerroGard corrosion protection calculated above. The concentrations measured are above this figure for all the specimens.

(The average figures from all the measurements were used to show the depth profiles.) The theoretical concentration limit of $0.1 \mu\text{g}$ FerroGard per gram of concrete is below the detection limit of $0.9 \mu\text{g}$ per gram of concrete.

Therefore, it is possible to define a "practical concentration limit" of $0.9 \mu\text{g}$ FerroGard per gram of concrete at which effective corrosion protection is guaranteed. Compared with the theoretical concentration limit, this gives a safety factor of 9 to compensate for any errors made with the idealized method of observation, the one used for calculation of the theoretical concentration limit.

4.4 Leaching behaviour

To investigate whether the FerroGard concentration in the concrete is high enough after weathering of structures, the leaching behaviour was examined in accelerated weathering tests. To evaluate the leaching behaviour of FerroGard, only the drop in the concentration in the concrete below the concentration limit is considered. The leaching behaviour of the protective film already formed on the steel has been satisfactorily tested in [4]. No significant decrease in the film thickness after watering was found.

The accelerated weathering tests on unprotected concrete specimens were carried out in a ventilated outdoor test chamber, both to create conditions which would be as realistic as possible in terms of temperature and moisture variations and to exclude the influence of natural precipitation (Fig 12 and Photo 2 of the photographic records).

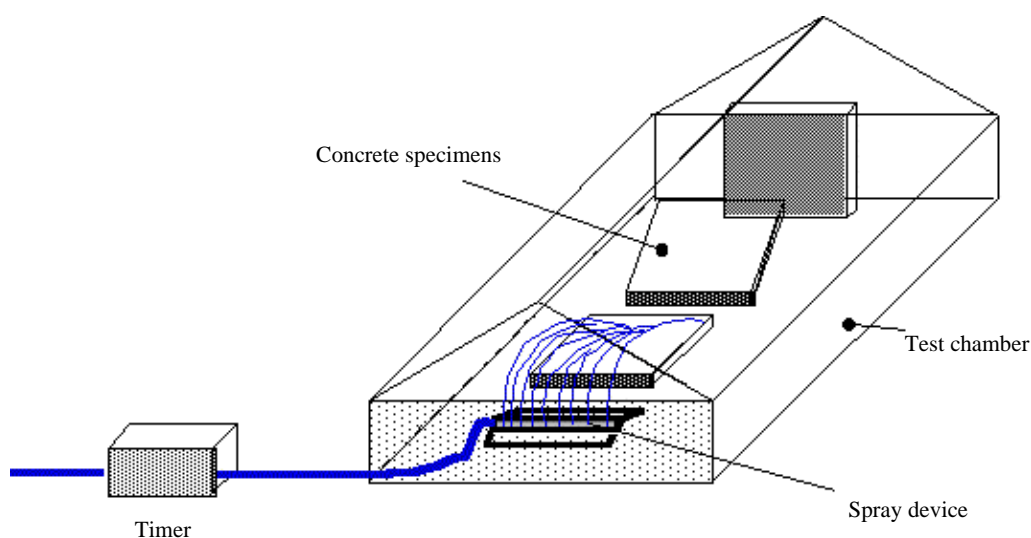


Fig 12: Test configuration for accelerated weathering.

The following 24-hour spraying cycle was set on a programmable timer (Photo 3, attached photographic records).

Spray for eight hours, dry for 16 hours, spray for eight hours, etc.

The volume of "rain" produced was about 250 l/m² per day. Assuming an average natural rain volume of about 1,200 l/m² per annum for the Zurich region, an accelerated weathering period of 30 days is equivalent to a natural weathering period of five years. Therefore an accelerated weathering period of 60 days is equivalent to a natural weathering period of ten years. Only the water volumes reaching the specimens are used to evaluate the leaching behaviour and other mechanisms which may be relevant are ignored.

Analysis

After the accelerated weathering the FerroGard content of the specimens was determined as described in section 4.3 (Table 4) and applied as a factor of the distance from the treated concrete surface. Fig 13 shows all the depth profiles obtained compared with the depth profiles of unweathered specimens. Fig 14 shows the same depth profiles with the concentration limits marked.

Sample No.	Depth [mm]	Nitrogen content [μ /g concrete]	FerroGard content [μ g/g concrete]	Leaching [days]
1	0 - 12.5	4.0	35.7	60
	12.5 - 25.0	1.0	8.9	
	25.0 - 37.5	0.7	6.3	
	37.5 - 50.0	0.1	0.9	
4	0 - 12.5	1.2	10.7	60
	12.5 - 25.0	1.3	11.6	
	25.0 - 37.5	1.9	16.9	
	37.5 - 50.0	0.1	0.9	
5	0 - 12.5	11	98.2	30
	12.5 - 25.0	11	98.2	
	25.0 - 37.5	6	53.5	
	37.5 - 50.0	3	26.8	
6	0 - 12.5	19	169.6	30
	12.5 - 25.0	1.0	8.9	
	25.0 - 37.5	0.9	8.0	
	37.5 - 50.0	0.5	4.5	
18	0 - 12.5	25	223.2	0
	12.5 - 25.0	0.7	6.3	
	25.0 - 37.5	0.1	0.9	
	37.5 - 50.0	0.1	0.9	
7	0 - 12.5	22	196.4	0
	12.5 - 25.0	0.8	7.1	
	25.0 - 37.5	1.0	8.9	
	37.5 - 50.0	1.1	9.8	

Table 4: FerroGard concentrations as a factor of the distance from the concrete surface

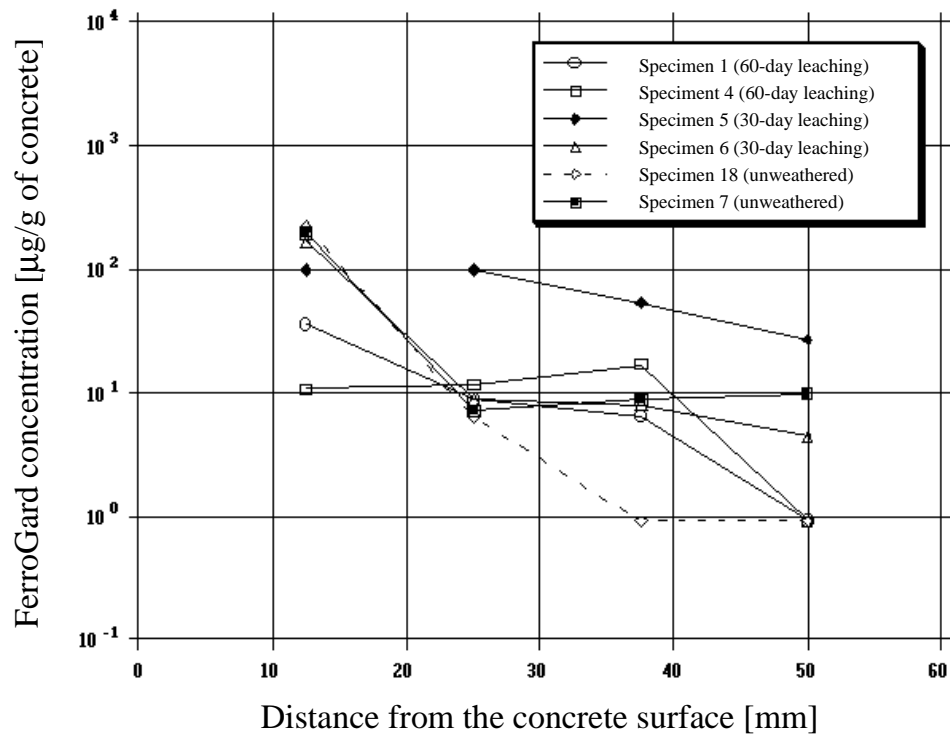


Fig 13: Depth profiles after accelerated weathering.

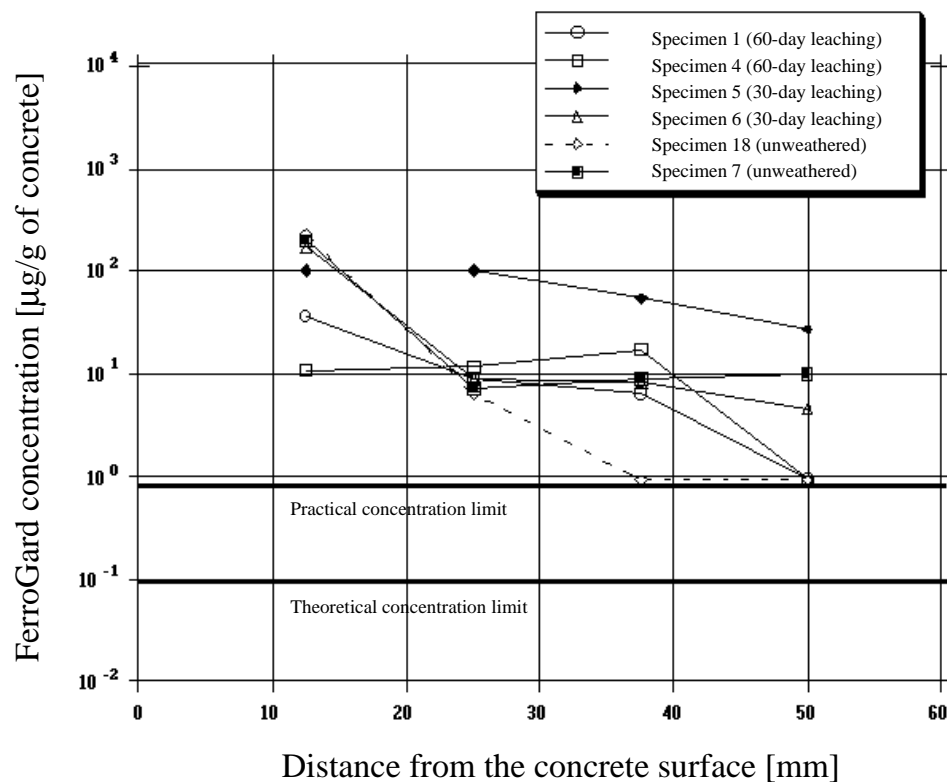


Fig 14: Depth profiles after accelerated weathering with theoretical and practical concentration limits marked.

Discussion

The above depth profiles show that even after a leaching period of 60 days, the rain volume of which is equivalent to ten years' natural weathering, FerroGard can be detected to a depth of 50 mm in a concentration which is above the level necessary for corrosion protection.

4.5 FerroGard penetration in concrete

The quantity of FerroGard which penetrates as a factor of the penetration depth is analysed below using a test method similar to water conductivity test SIA 162/1, test No. 5. This was done to examine whether the penetration capacity is determined only by capillary suction forces or also by other transport mechanisms.

Test configuration

The cores were dipped in FerroGard 903 solution and stored in a sealed chamber to ensure an atmospheric humidity of more than 95% during the absorption test.

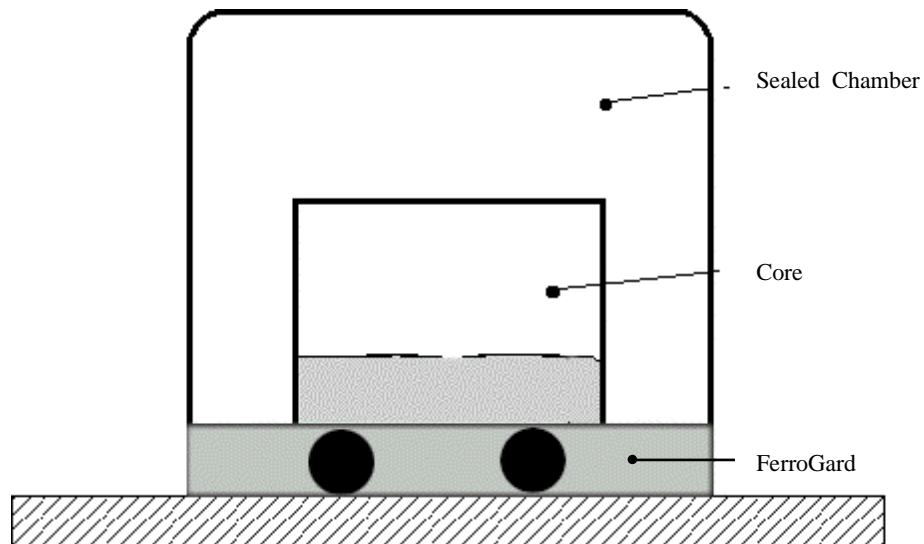


Fig 15: Absorption test configuration.

Test method

- . Dry test specimens at 50°C for two days.
- . Cool test specimens for one day at room temperature.
- . Weigh test specimens => M_{50}
- . Dip test specimens 3 mm into FerroGard 903 at approx. 20°C in a sealed container (approx. 95% RH).
- . Weigh test specimens after different times => M_t .
- . Store test specimens for at least seven days in FerroGard (approx. 20°C).
- . Weigh test specimens => M_E .

Definitions

M_{50}	Mass of test specimen after 2 days' drying at 50°C
M_t	Mass of test specimen after FerroGard absorption after a time t (3 mm in solution)
M_E	Mass of test specimen after 7 days' FerroGard storage (= capillary pores fully saturated)
H	Test specimen height
h_t	Capillary rise after the time t

Analysis

Calculation of capillary rise after the time t:

$$h_t = H * (M_t - M_{50}) / (M_E - M_{50}) \text{ [mm]}$$

The test report with the capillary porosity figures and calculation of the capillary rises is in the Appendix (Reports 1 and 2)

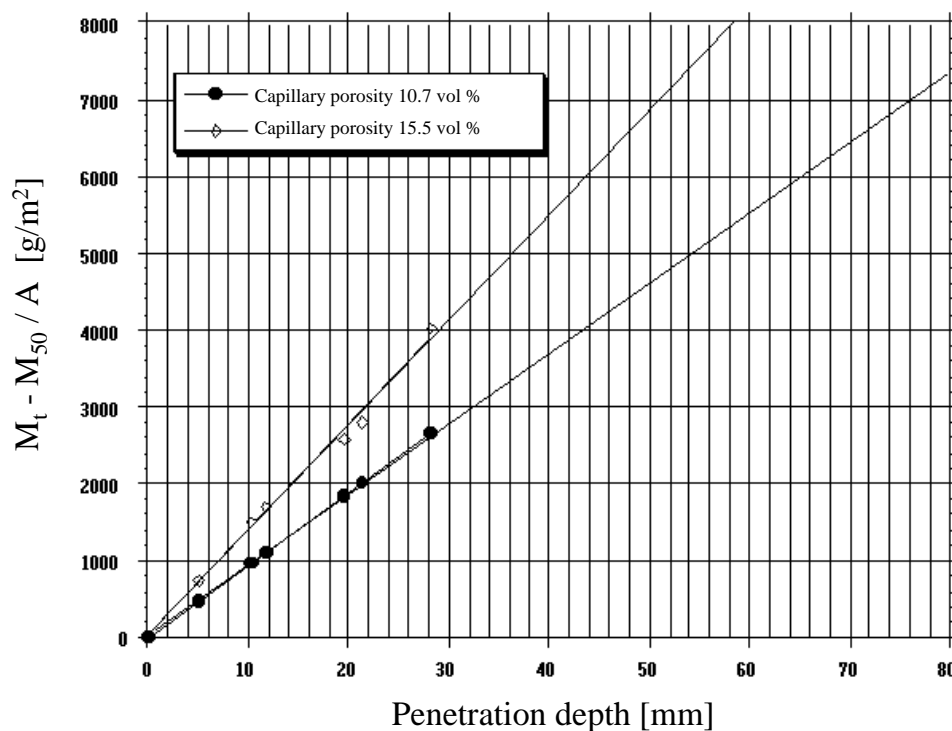


Fig 16: Penetration depth as a factor of the quantity of FerroGard 903 applied.

From the capillary rises for the time t , diagrams of $(M_t - M_{s0})/A$ (FerroGard quantity applied per square metres) were drawn using the capillary rise h_t (penetration depth). The diagrams are shown in Fig 16 for two specimens with different capillary porosity.

It can be seen that a penetration depth of less than 10 mm is obtainable with a FerroGard quantity applied of 500 g/m^2 , but in section 4.2 FerroGard was detected to a depth of 50 mm after application of 500 g/m^2 . This shows that capillary suction alone is not responsible for the penetration capacity. The penetration mechanism is an interaction between capillary suction and diffusion through the liquid phase and through the gas phase, resulting in much greater penetration depths.

4.6 Examination of incipient anode formation

If the protective film formed on the steel by FerroGard is non-homogeneous, i.e. FerroGard does not penetrate evenly to the reinforcement when a reinforced concrete structure is impregnated, is there a risk in principle of incipient anode formation? (Figs 17 and 18). To investigate this problem, 12 test specimens measuring $150 \times 150 \times 500 \text{ mm}$ with three reinforcing bars of $\varnothing 12 \text{ mm}$ were produced. The concrete cover was 30 mm (Fig 20 and Photos 4 and 5 of the attached photographic records). The reinforcing bars had surface corrosion before placement.

Both carbonation corrosion and chloride-induced corrosion were simulated. Some of the specimens were subjected to accelerated carbonation after FerroGard application and others were produced with a higher chloride content (0.4 and 1.0 wt.%). The specimens and their treatment or chloride content are listed in Table 5. FerroGard solution (500 g/m^2) was applied to half the specimens on one side to simulate non-homogeneous corrosion protection film formation on the steel (Fig 19).

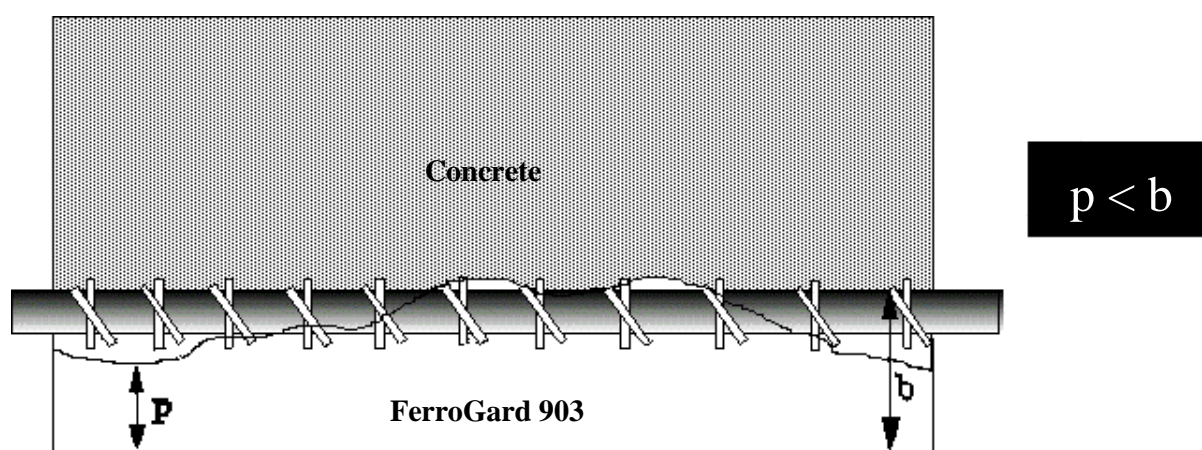


Fig 17: Risk of incipient formation on reinforcement partially impregnated with FerroGard.

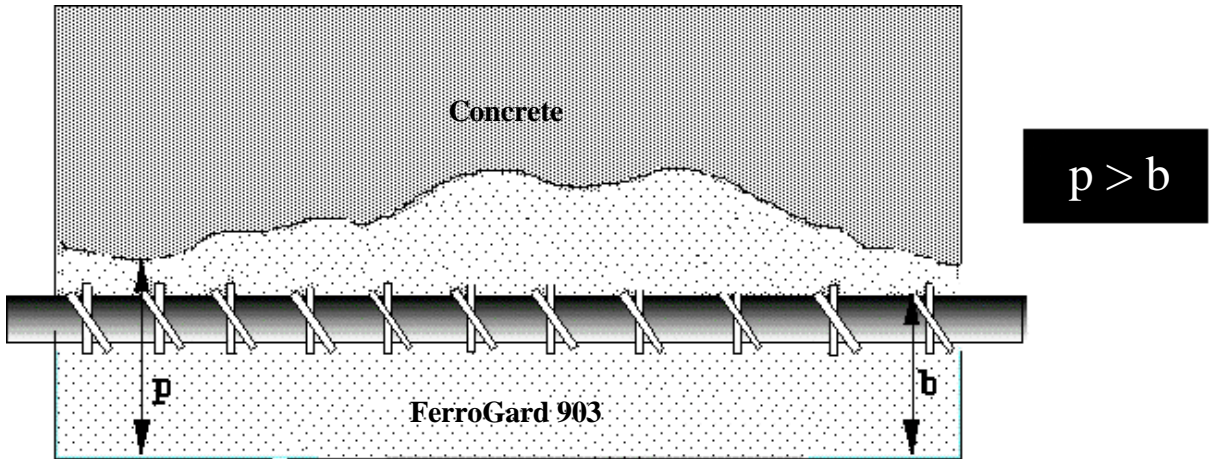


Fig 18: No incipient anode formation on reinforcement fully impregnated with FerroGard.

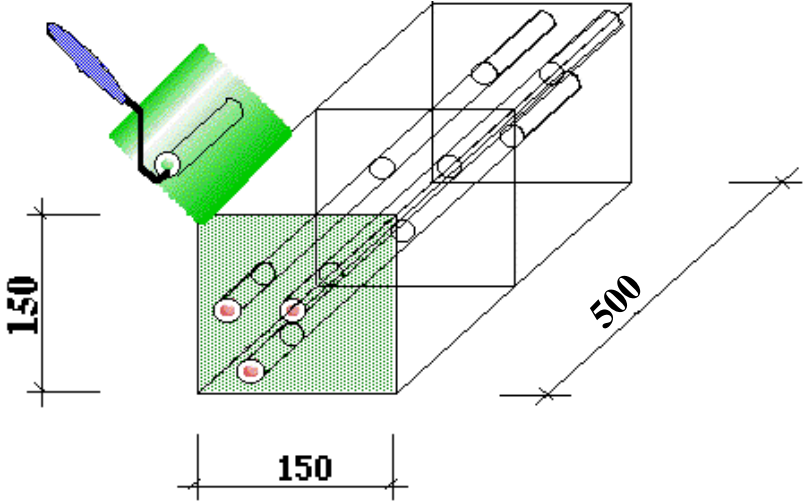


Fig 19: Test configuration for analysis of the incipient anode formation

Test sample	W/C ratio	Chloride content [%]	Storage	Application
1	0.45	0	CO2 (accelerated carbonation)	FerroGard 1 side
2	0.45	0	CO2 (accelerated carbonation)	Untreated
3	0.60	0	CO2 (accelerated carbonation)	FerroGard 1 side
4	0.60	0	CO2 (accelerated carbonation)	Untreated
5	0.60	1.0	Air (23°C / 50% RH)	FerroGard 1 side
6	0.60	1.0	Air (23°C / 50% RH)	Untreated
7	0.45	1.0	Air (23°C / 50% RH)	FerroGard 1 side
8	0.45	1.0	Air (23°C / 50% RH)	Untreated
9	0.60	0.4	Air (23°C / 50% RH)	FerroGard 1 side
10	0.60	0.4	Air (23°C / 50% RH)	Untreated
11	0.45	0.4	Air (23°C / 50% RH)	FerroGard 1 side
12	0.45	0.4	Air (23°C / 50% RH)	Untreated

Table 5: List of all specimens for analysis of incipient formation.

To assess the corrosion state of the reinforcement and therefore any incipient anode formation, the steel was visually inspected and spot potential measurements were taken over a period of three months.

Visual inspection

Sounding openings were made in the specimens with a chloride content of 0.4 or 1.0 wt.% and the reinforcing steel cross-section was examined for corrosion (Photos 6 to 9 of the photographic records).

Spot potential measurements

The electrochemical potentials of the specimens were determined periodically from 16 October 1996 to 24 January 1997 (Photo 10, attached photographic records) and shown as digital colour plots on a measuring grid. The environmental conditions were kept constant throughout the test (23°C / approx. 50% RH). The digital colour plots appear in the Appendix.

Discussion

- . The corrosion state of the reinforcement does not change measurably over the three-month period in specimens 1-4 subjected to accelerated weathering. Very little difference can be found between the specimens treated with FerroGard and the untreated specimens.
- . The potentials rise slightly in specimens 5-12 treated with chloride. This rise also occurs in the untreated specimens. The reason is probably that the samples dry out under the environmental conditions in the laboratory (23°C / approx. 50% RH) and the corrosion flows are relatively low.
- . The visual inspection of the reinforcing steel cross-section and the spot potential measurements have to date shown no sign of corrosion and there is no suggestion of incipient anode formation due to FerroGard application on one side.
- . A general comment on the above test series is that the corrosion rate under laboratory conditions at a temperature of 23°C and relative humidity of 50% is relatively low despite high chloride contents and carbonation levels. A longer test period and weathering is necessary before reliable statements can be made on incipient anode formation. The specimens will be stored outdoors for further observation. The additional results will be supplied later as an addendum to this report.

5. Behaviour of FerroGard solution towards construction materials

The following is a list of the materials frequently used in building and their resistance to alkaline solutions such as FerroGard (pH≈11):

Silicone rubber

Silicone rubber is resistant to dilute alkalis, weak acids and aqueous solutions of inorganic salts but is destroyed by concentrated acids and alkalis. Silicone rubber is resistant to 10% but not 50% caustic soda.

Butyl rubber

This material is extremely resistant to aqueous solutions of inorganic salts, acids and bases. Butyl rubber is resistant to 50% caustic soda (NaOH), even at 60°C.

PVC

Flexible PVC has only limited resistance to strong bases because it contains plasticizers. These normally consist of volatile substances which can be dissolved more or less easily out of the PVC. Rigid PVC has extremely high resistance to strong acids and bases.

Polyethylene (PE)

Polyethylene has generally good chemical resistance to weak acids and concentrated bases, with HDPE being more resistant than LDPE.

Epoxy resin (EP)

Epoxy resin has only limited resistance to attack from strong bases.

Polyurethane (PUR)

Chemical attack from strong bases can cause decomposition of PUR by hydrolysis.

Glass

Glass has a marked three-dimensional structure which contains silicon dioxide tetrahedrons as basic building blocks. Alkaline or alkaline earth oxides are also built in to obtain the properties required. The critical factor for glass decomposition is the pH value of a solution. The corrosion rate is constant and low in a wide pH range but the reaction speed increases above a pH of 9.

Aluminium

In air, aluminium becomes covered with a fine but very strong coating of aluminium oxide. This is dense and pore-free and protects the metal from further oxidation, giving it high corrosion resistance, but this can only be guaranteed for a pH range of between 5 and 8. Strong alkaline solutions cause surface decomposition of the aluminium. Aluminium is a material which cannot normally be used with pH values of less than 4.5 or more than 8.5.

Copper

The effect of highly alkaline solutions is to promote verdigris formation in copper. Aesthetic problems may result.

Steel

Steel is generally used unalloyed as a building material and is therefore not normally protected against corrosion. In an alkaline environment only (e.g. in concrete) with a pH > 12, steel becomes spontaneously coated with a stable passive layer providing extremely good corrosion protection. This layer is stable up to a pH value of 9.5 (passivation limit).

Galvanized steel

The zinc layer is attacked and broken down by effect of the FerroGard solution.

Timber

Timber is a material which consists mainly of cellulose fibre, a binder, lignin and voids. Impregnation of timber with a strong base has two effects: Firstly, swelling due to the voids being filled and secondly gradual dissolution of the binder.

On the basis of the above descriptions, the following recommendations can be made:

Material	Recommended Site Precaution
Silicone rubber	Cover
Butyl rubber	Do not cover
Rigid PVC	Do not cover
Flexible PVC	Cover
Polyethylene (PE)	Do not cover (can be used as cover sheet)
Epoxy resin (EP)	Cover
Polyurethane (PUR)	Cover
Glass	Do not cover
Aluminium	Cover
Copper	Cover
Steel	Do not cover
Galvanized steel	Cover
Timber	Cover

Table 6: Protective measures during application of the highly alkaline FerroGard 903 solution adjacent to materials commonly used in buildings.

6. Optimization of application technique

The following recommendations should be followed to optimize the application technique:

- . The FerroGard solution must penetrate as deeply as possible.
- . The water saturation level and capillary porosity generally determine the capillary absorption behaviour of concrete towards liquids, but these parameters are less relevant to FerroGard penetration because other transport mechanisms are also involved.
- . The FerroGard 903 consumption should be defined, monitored and checked.

This gives the following instructions for application:

To achieve maximum penetration of FerroGard 903, make sure that in addition to the diffusion characteristics (which cannot be further influenced by the application) the capillary suction effect is as high as possible. To achieve this, the concrete should be allowed to dry out between the various applications. Three to five operations are recommended. Ensure also that movement into the deeper concrete layers can continue after the last operation.

7. Quality assurance measures during the works

To prevent any risk of incipient anode formation by partial protective film formation during later impregnation of the concrete with FerroGard (Figs 20 and 21), the quality assurance concept described below has been developed for use during the works. To date there is no way of proving the effectiveness at a later date by non-destructive methods. Analysis of the electrochemical potential or corrosion flow density after application does not achieve this objective because reliable statements on the corrosion protection effect can only be made by these methods after a long period and the effect of the concrete moisture on the test results is considerable. It is therefore essential to take cores after application as part of a sound quality assurance system.

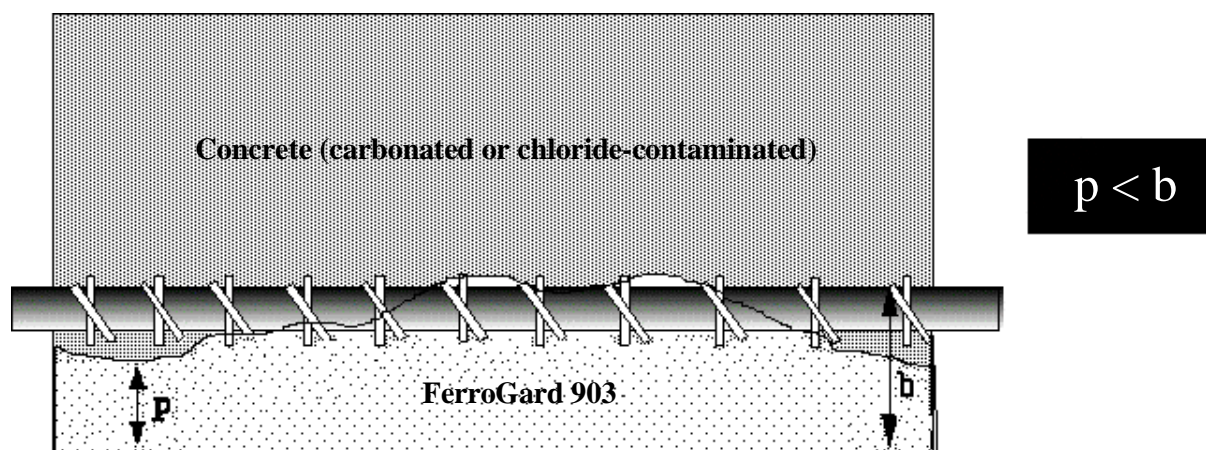


Fig 20: Risk of incipient anode formation on reinforcement partially impregnated with FerroGard 903.

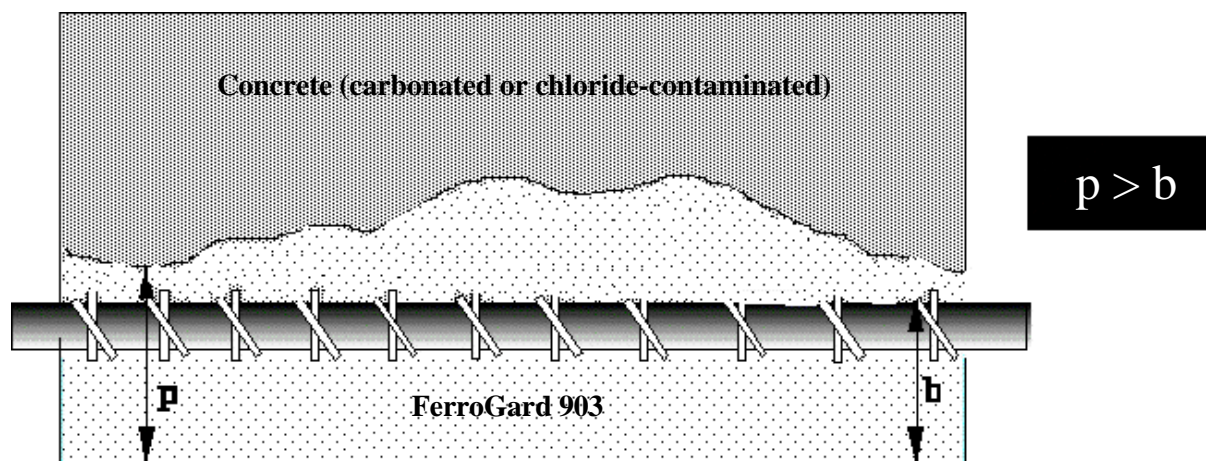


Fig 21: No incipient anode formation on reinforcement fully impregnated with FerroGard 903.

The concept is listed step by step below

- Full analysis of condition before repairs. Measurement of the concrete cover and carbonation depth.

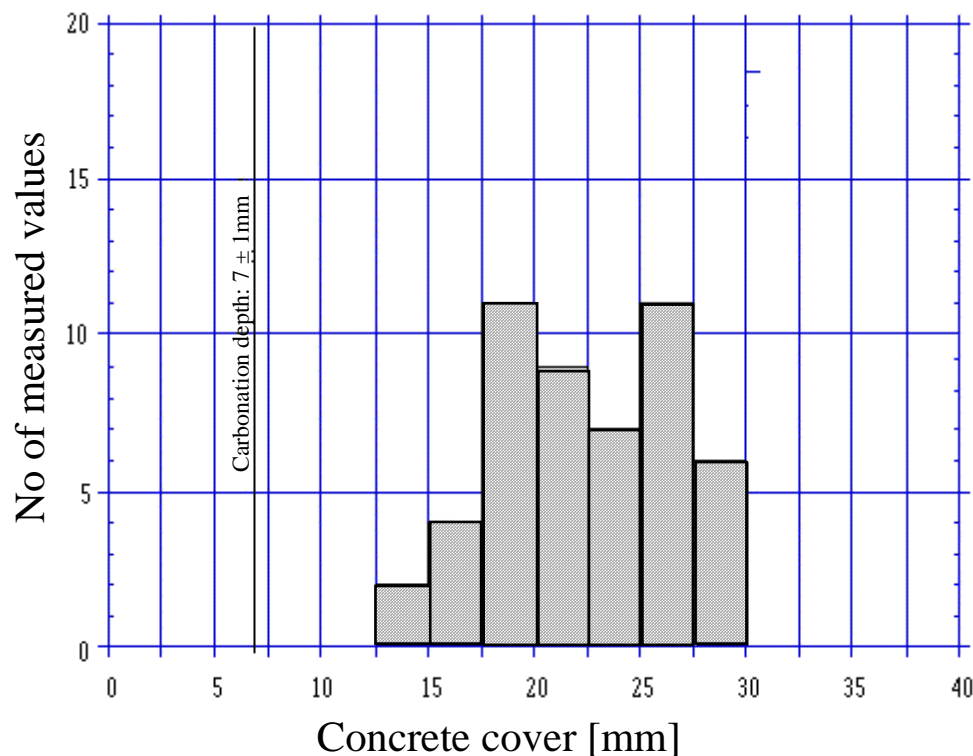


Fig 22: Measuring the concrete cover and carbonation depth before repairs.

- Determine the minimum necessary penetration depth p of FerroGard from the reinforcement cover plus the reinforcement diameter b , as shown in Figs 20 and 21. The criterion $p > b$ should be met in areas on the structure where the steel reinforcement passivation layer is at risk from carbonation or a high chloride concentration in the concrete.
- Apply the quantity of FerroGard per square metre specified in the contract to a reference surface on the structure.
- Apply the specified quantity of FerroGard-903 usually in three to five operations.
- Take cores after application. Calculate the FerroGard consumption from the FerroGard contents in the reference surface and on the structure using quantitative laboratory

analyses. The calculated consumption on the structure must be the same as the consumption on the reference surface.

Draw depth profiles and mark the minimum FerroGard concentration (Fig 23). As stated in Section 4.3, the theoretical minimum FerroGard concentration is $0.1 \mu\text{g}$ per gram of concrete. The FerroGard detection limit is $0.9 \mu\text{g}$ per gram of concrete. This concentration was defined in Section 4.3 as the minimum practical concentration. The criterion for application can therefore be defined as follows: "Down to the minimum penetration depth p , FerroGard must be detected by the method of analysis described in 4.2", to ensure effective corrosion protection. Alternatively, depth profiles can be produced using a qualitative detection method developed by Sika AG (colour test).

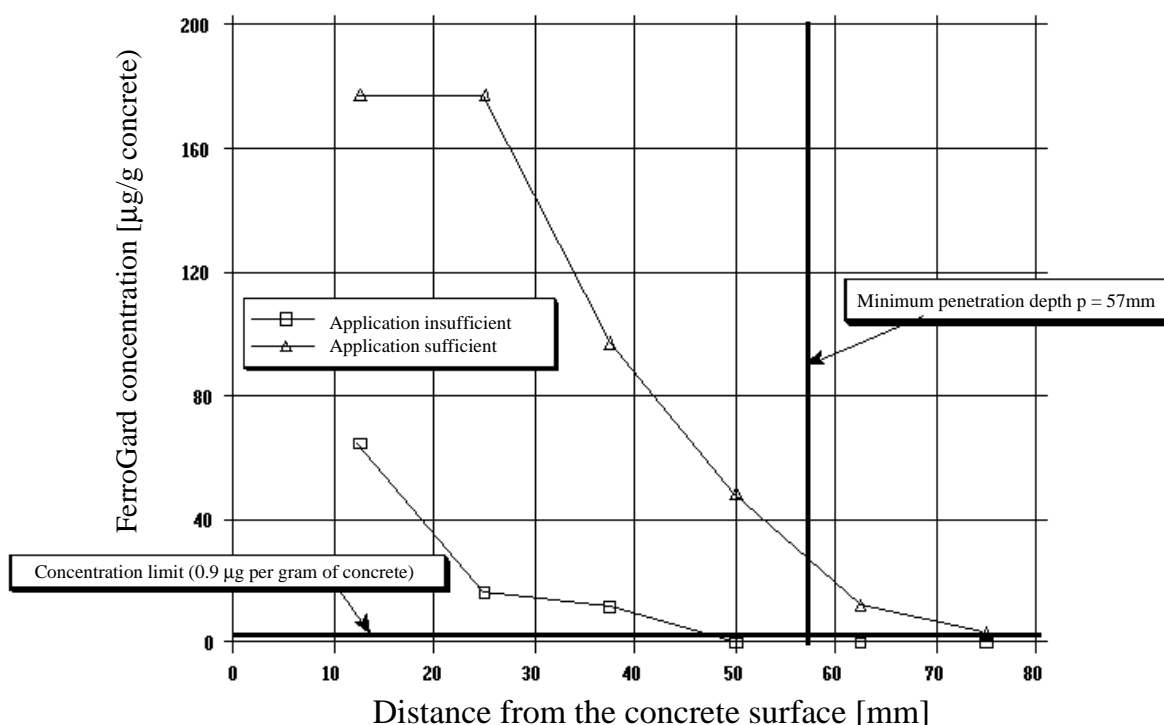


Fig 23: Example of a depth profile with minimum penetration depth of 57 mm marked

If the penetration depth is insufficient, deeper penetration can be obtained by watering or repeating the application.

8. Evaluation

- . The tests carried out show that FerroGard 903 can be detected analytically after application on concrete specimens to a minimum depth of 50 mm after extraction and analysis of the nitrogen content.
- . The protective film thickness on the steel necessary for effective corrosion protection is only about 10 nm. The FerroGard concentration calculated from this, based on the concrete weight, is 0.1 µg per gram of concrete. This figure is below the detection limit of the analysis method described. In general, therefore, it can be said that application of the active corrosion inhibitor FerroGard-903 is an extremely effective method of corrosion protection of steel reinforcement because the protective film required is very thin.
- . The effect of the carbonation level, capillary porosity and water saturation level on the penetration capacity of FerroGard, evaluated by later analysis of the FerroGard concentration as a factor of the depth, is insignificant.
- . Even after an accelerated weathering period of 60 days, equivalent to a natural weathering period of ten years, FerroGard was detected down to a depth of 50 mm, so that the corrosion protection effect of FerroGard is preserved. It has also been shown in [4] that the protective film already adhering to the steel is extremely resistant to weathering (leaching).
- . The risk of incipient anode formation can be ruled out on the basis of tests to date, provided that a comprehensive quality assurance system is in place on the site.
- . Given compliance with the safety and application instructions and application of a quality assurance concept during the works, Sika FerroGard-903 is a technically simple, effective and durable method of repairing reinforced concrete structures.

9. Recommendation

- . The theoretical calculations in this report to find the minimum FerroGard concentration in the concrete necessary for effective corrosion protection should be checked and firmed up by future experience in the field during application to structures.
- . The quality assurance concept described should be applied in future to repairs on reinforced concrete structures with FerroGard-903 and supplemented or adapted as additional field experience becomes available.

Appendix

Photographic Records



Photo 1
Accelerated carbonation in a CO₂ rich atmosphere



Photo 2
Accelerated weathering by defined spraying of specimens



Photo 3
Timer to control spraying



Photo 4
Application of FerroGard-903 on one side of specimens

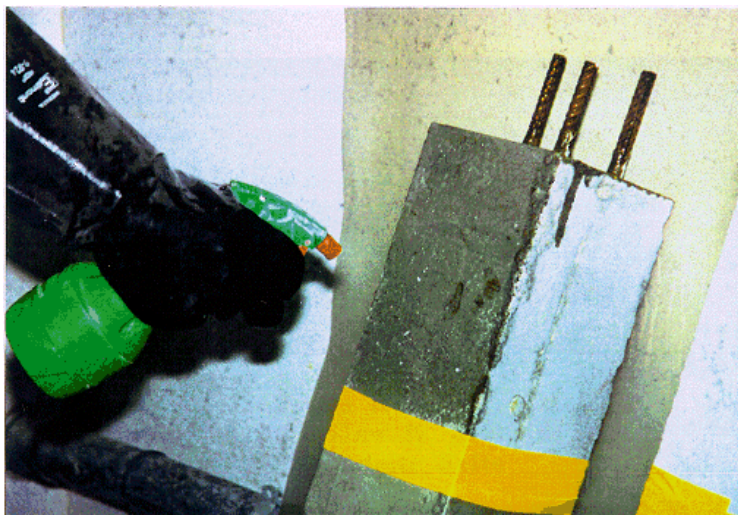


Photo 5
Application of FerroGard-903 with low-pressure hand spray



Photo 6
Bright steel cross-sectional area of sample No. 9, untreated side

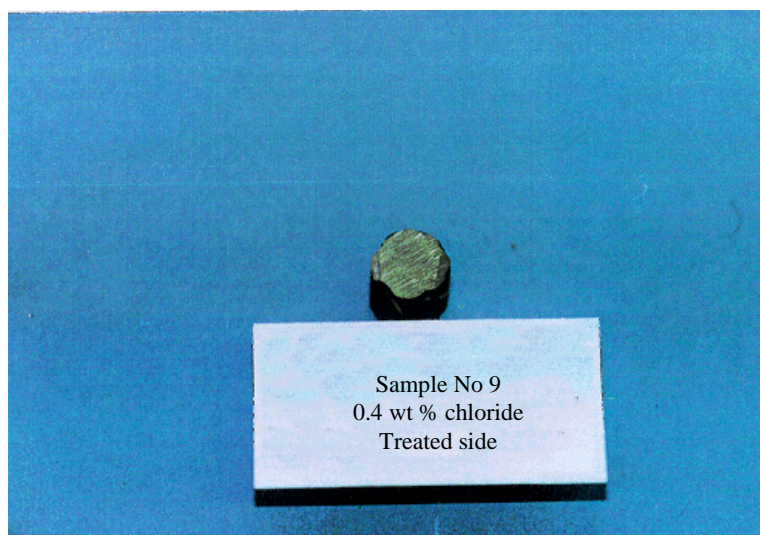


Photo 7
Bright steel cross-sectional area of sample No. 9, side treated with FerroGard 903

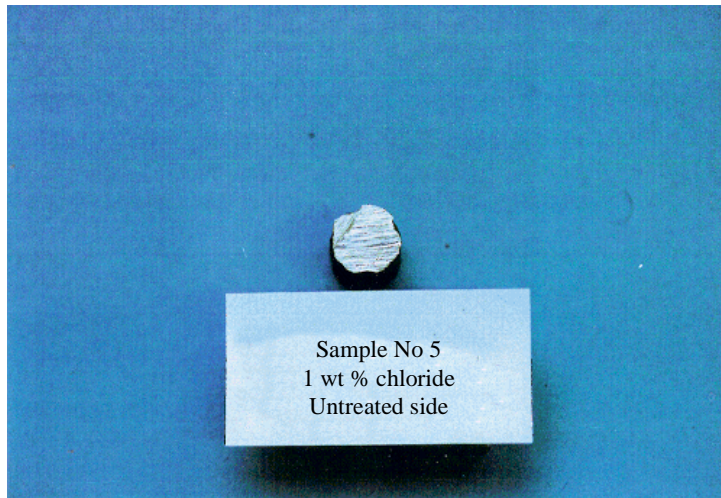


Photo 8

Bright steel cross-sectional area of sample No. 5, untreated side

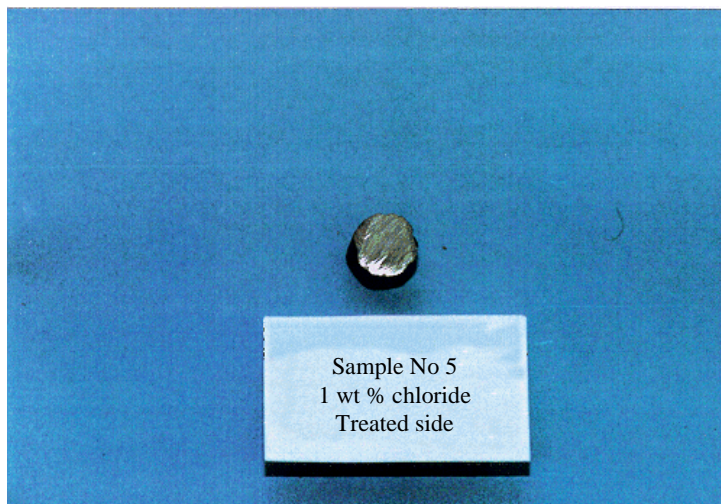


Photo 9

Bright steel cross-sectional area of sample No. 5, side treated with FerroGard-903

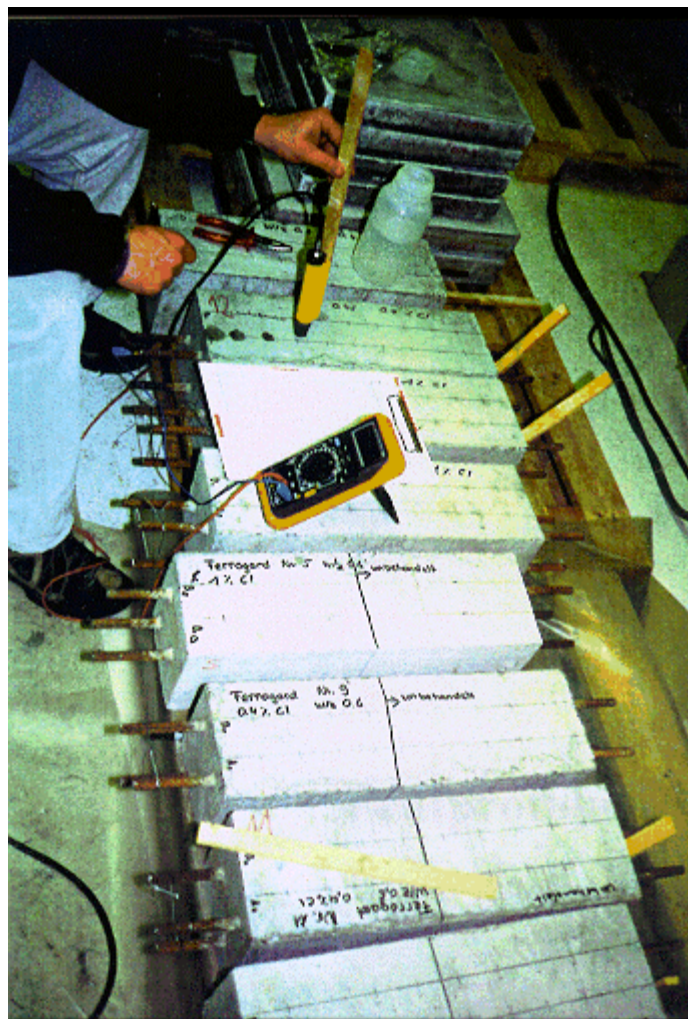


Photo 10

Spot potential measurement to check for incipient anode formation

Test Reports

Wolfseher und Partner AG

Consultant Material Technologists and Construction Engineers

Report 1

Project: 96.144.1 Zurich, Sika FerroGard

Capillary Porosity to SIA 162/1 No. 7

Test material: Concrete test slabs

Date: 13.12.1996 / IS

Sample No and W/C	MA [g]	M50 [g]	ME [g]	M under W [g]	VE [cm ³]	M105 [g]	Dry density rR105 [kg/m ³]	Water content U50 [vol - %]	Content of fillable pores UE [vol %]
1 0.6	138.347	135.2447	143.6452	85.1	58.5	134.5917	2301	1.1	15.5
2 0.6	138.8407	136.6118	144.5852	85.6	59.0	136.0055	2305	1.0	14.5
3 0.6	137.2824	135.3059	142.6774	85.1	57.6	134.8077	2340	0.9	13.7
4 0.6	144.5027	141.7520	149.0750	89.2	59.9	141.1061	2356	1.1	13.3
5 0.6	136.1395	133.5658	140.8744	83.7	57.2	132.9220	2324	1.1	13.9
6 0.45	141.6411	139.4619	145.2400	87.5	57.7	138.0736	2393	2.4	12.4
7 0.45	143.7723	141.5254	147.0625	89.6	57.5	140.9187	2451	1.1	10.7
8 0.45	140.7234	138.2391	145.0426	86.6	58.4	137.0023	2346	2.1	13.8
9 0.45	136.659	134.1549	141.0176	84.1	56.9	132.9560	2337	2.1	14.2
10 0.45	141.2708	139.1682	145.7559	87.8	58.0	138.6392	2390	0.9	12.3

Wolfseher und Partner AG

Consultant Material Technologists and Construction Engineers

Report 2

Project:96.144.1 Zurich, Sika AG, FerroGard

Component: Slabs

Porosity to SIA 162/1 No. 7

Test material: Cores

Date: 7.1.1996

Notes: MA to M90.5 = Water absorption test

M90.5 to M426.3 (ME) = Underwater storage

$$ht = H^{\circ} (Mt - M50)/(ME - M50)$$

Sample No.: 1

Name of measurement	Time [h}	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			138.3470	30.0000	
M50=M0	0.00	0.00	135.2447		0.0000
M0.5	0.50	0.71	136.7035		5.2097
M3.0	3.00	1.73	138.1700		10.4469
M4.5	4.50	2.12	138.5758		11.8961
M19.6	19.58	4.43	140.3036		18.0664
M25.3	25.30	5.03	140.7268		19.5778
M90.5	90.50	9.51	143.1258		28.1451
M426.3=ME	426.25	20.65	143.6452		30.0000

Sample No.: 2

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			138.8407	30.0000	
M50=M0	0.00	0.00	136.6118		0.0000
M0.5	0.50	0.71	137.9051		4.8661
M3.0	3.00	1.73	139.1594		9.5854
M4.5	4.50	2.12	139.4857		10.8131
M19.6	19.58	4.43	141.0903		16.8504
M25.3	25.30	5.03	141.5056		18.4130
M90.5	90.50	9.51	143.7556		26.8786
M426.3=ME	426.25	20.65	144.5852		30.0000

Sample No.: 3

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			137.2824	30.0000	
M50=M0	0.00	0.00	135.3059		0.0000
M0.5	0.50	0.71	136.5731		5.1572
M3.0	3.00	1.73	137.8953		10.5382
M4.5	4.50	2.12	138.2213		11.8649
M19.6	19.58	4.43	139.7917		18.2560
M25.3	25.30	5.03	140.1889		19.8725
M90.5	90.50	9.51	142.2700		28.3420
M426.3=ME	426.25	20.65	142.6774		30.0000

Sample No.: 4

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			144.5027	30.0000	
M50=M0	0.00	0.00	141.7520		0.0000
M0.5	0.50	0.71	142.8922		4.6710
M3.0	3.00	1.73	144.0577		9.4457
M4.5	4.50	2.12	144.3323		10.5707
M19.6	19.58	4.43	145.7613		16.4248
M25.3	25.30	5.03	146.1444		17.9943
M90.5	90.50	9.51	148.2700		26.7022
M426.3=ME	426.25	20.65	149.0750		30.0000

Sample No.: 5

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			136.1395	30.0000	
M50=M0	0.00	0.00	133.5658		0.0000
M0.5	0.50	0.71	134.7214		4.7435
M3.0	3.00	1.73	135.8348		9.3137
M4.5	4.50	2.12	136.1170		10.4720
M19.6	19.58	4.43	137.5095		16.1879
M25.3	25.30	5.03	137.9406		17.9575
M90.5	90.50	9.51	139.7432		25.3567
M426.3=ME	426.25	20.65	140.8744		30.0000

Sample No.: 6

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			141.6411	30.0000	
M50=M0	0.00	0.00	139.4619		0.0000
M0.5	0.50	0.71	140.0680		3.1469
M3.0	3.00	1.73	140.7052		6.4552
M4.5	4.50	2.12	140.8255		7.0798
M19.6	19.58	4.43	141.6078		11.1416
M25.3	25.30	5.03	141.8469		12.3830
M90.5	90.50	9.51	143.1757		19.2821
M426.3=ME	426.25	20.65	145.2400		30.0000

Sample No.: 7

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			143.7723	30.0000	
M50=M0	0.00	0.00	141.5254		0.0000
M0.5	0.50	0.71	142.4513		5.0165
M3.0	3.00	1.73	143.4316		10.3278
M4.5	4.50	2.12	143.6981		11.7717
M19.6	19.58	4.43	145.1304		19.5319
M25.3	25.30	5.03	145.4740		21.3935
M90.5	90.50	9.51	146.7446		28.2776
M426.3=ME	426.25	20.65	147.0625		30.0000

Sample No.: 8

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			140.7234	30.0000	
M50=M0	0.00	0.00	138.2391		0.0000
M0.5	0.50	0.71	139.0713		3.6696
M3.0	3.00	1.73	139.9474		7.5327
M4.5	4.50	2.12	140.1293		8.3348
M19.6	19.58	4.43	141.2708		13.3683
M25.3	25.30	5.03	141.6041		14.8380
M90.5	90.50	9.51	143.3012		22.3213
M426.3=ME	426.25	20.65	145.0426		30.0000

Sample No.: 9

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			136.6590	30.0000	
M50=M0	0.00	0.00	134.1549		0.0000
M0.5	0.50	0.71	135.0424		3.8797
M3.0	3.00	1.73	135.9024		7.6391
M4.5	4.50	2.12	136.0938		8.4758
M19.6	19.58	4.43	137.1638		13.1533
M25.3	25.30	5.03	137.4981		14.6147
M90.5	90.50	9.51	138.9888		21.1312
M426.3=ME	426.25	20.65	141.0176		30.0000

Sample No.: 10

Name of measurement	Time [h]	Time [✓ h]	Mt [g]	Height H of core [mm]	Capillary rise ht [mm]
MA			141.2708	30.0000	
M50=M0	0.00	0.00	139.1682		0.0000
M0.5	0.50	0.71	140.4212		5.7061
M3.0	3.00	1.73	141.8720		12.3129
M4.5	4.50	2.12	142.2633		14.0949
M19.6	19.58	4.43	144.3630		23.6568
M25.3	25.30	5.03	144.7872		25.5886
M90.5	90.50	9.51	145.4829		27.7568
M426.3=ME	426.25	20.65	145.7559		30.0000

Proof Statements

Wolfseher and Partners

General

Key Conclusions

- ▲ **Penetrates carbonated concrete at varying mc's and porosity**
- ▲ **Resistant to leaching (10 years)**
- ▲ **Prevents incipient anode formation**
- ▲ **Building materials have to be protected during application**