



TECHNICAL ARTICLE

CORROSION TESTS ON CRACKED CONCRETE BEAMS

Adapted from ASTM G109

JULY 2018 / VERSION 2 / SIKA SERVICES AG / MICHEL DONADIO

External diffusion

BUILDING TRUST



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1 INTRODUCTION

The steel reinforcement in concrete starts to corrode in the presence of moisture when the passive layer formed by the surrounding highly alkaline concrete matrix has broken down due to carbonation, or the presence of chlorides.

To initiate an electrochemical process, several elements are required to be present:

- A loss of passivity (due to carbonation or presence of chlorides),
- moisture,
- and oxygen.

Deeply penetrating, surface applied, hydrophobic impregnation silane based materials, such as the liquid applied **Sikagard®-705 L**, or the cream consistency **Sikagard®-706 Thixo**, will reduce the moisture level around the reinforcement bars and therefore this will also reduce any corrosion activity. Additionally, these products will prevent further ingress of chloride ions into the structure.

This technical article is written using the information provided by the laboratory report reference 5475/V2 by Sika Technology AG dated February 25th, 2016

2 METHODOLOGY

The cracked concrete beam corrosion test (CCBCT) is a laboratory time-to-corrosion test. It was developed by Paul Tourney and Neal Berke[1]. The test is adapted from ASTM G109[2].

2.1 PRODUCT

Sikagard®-705 L was selected for this test as for a laboratory study application of a liquid can be controlled and it is similar in nature to the product X tested.

Product X claims to be a corrosion inhibitor from an international manufacturer.

2.2 PREPARATION OF REINFORCING STEEL BARS

To prevent crevice corrosion during the test, the reinforcing steel bars are prepared as followed:

- Type: Grey mild steel reinforcing rods, grade S235JR+AR (EN 10025-2:2004-10)
- Dimension: Diameter 12 mm, length 914 mm
- Preparation: Removal of rust particles mechanically with a power wire brush
Degreasing the bars with acetone
Both ends (203 mm – 8 in) of the rod are coated with epoxy
Both ends are further protected against crevice corrosion with a heat shrink tube

2.3 MIX DESIGN

Production of concrete according to EN 1766

Cement CEM I 42.5 N: 355 kg/m³

Aggregates 0-16 mm

W/C: 0.40

Flow table spread: 33-36 cm

Air content: 1.6 to 2.4 %

Curing after demolding: 20°C 95% RH

2.4 CONCRETE SPECIMENS

The test specimens are concrete beams of the size 150 x 150 x 750 mm (6 x 6 x 30 in) with three embedded 12 mm diameter mild steel rebars. Two rebars are placed 38 mm (1.5 in) from the bottom of the beams, the third 43 mm (1.7 in) below the top surface of the beams.

No mould release agent was used during production of beams in order not to interfere with the penetration of the hydrophobic impregnation.

After curing the specimens in a humidity chamber for 28 days and then subsequent storage for a month at approximately 23°C, a 5 mm (0.2 in) deep and 3 mm (0.1 in) wide groove was sawn into the top of the mini-beams. The resulting concrete cover, measured below the notch, is 38 mm (1.5 in).

The sides and the bottom of the beams were coated with two coats of epoxy resin (Sikagard®-63) in order to limit water evaporation (simulation of a bridge or parking garage deck) and to prevent contamination from spills of chloride solution during cyclic ponding.

The bottom rebars were permanently connected to each other with 1.0 mm diameter copper wire, and the top rebars are electrically short-circuited using a 10-ohm resistor soldered to the copper wire.

A Plexiglas dyke, 305 mm long, 114 mm wide and 51 mm deep, is attached to the top surface of the cracked beams and sealed with SikaBond AT-14. The dyke is used to expose the beams to a 3.0% (5.0%) by mass solution of sodium chloride using a 2-week wet, 2-week dry ponding cycle procedure. During the wet cycle, the dyke is filled to within 20 mm off the top with sodium chloride solution. The dyke is covered with a plastic plate in order to avoid water evaporation.

Average time period between the end of the 28-day curing period and the subsequent cracking procedure: 2 months (average time period between casting and cracking the beams: 3 months).

Average time period between the end of the 28-day curing period and the start of the first ponding cycle: 3 months (average time period between casting the beams and the beginning of the first ponding cycle: 4 months). After curing all specimens were stored in the lab at about 23°C.



2.5 CONCEPT OF TESTING

The products to be tested are applied at different intervals and mimic different scenarios taking place in the field:

- **Before** artificial cracking and **Before** corrosion initiation (B/B)
- **After** artificial cracking and **Before** corrosion initiation (A/B)
- **After** artificial cracking and **After** corrosion initiation (A/A)

2.6 ARTIFICIAL CRACKING PROCEDURE

Each beam was carefully cracked along the groove using flexural load bearing techniques, so that the crack extends down to the top rebar. Whilst under the cracking load, the crack is shimmed to a consistent crack size to be used throughout the whole corrosion test. For this purpose three to four 0.25 mm (0.01 in) thick stainless steel shims are inserted into the crack to hold it open once the load is released



2.7 APPLICATION PROCEDURE

The products for testing were applied by brush in two coats of 150 g/m² for Sikagard®-705 L and in three coats of 167 g/m² each for Sikagard®-705 L and Product X (typically recommended consumptions) resulting in totals of 300 and 500 g/m² respectively.

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2.8 PONDING PROCEDURE

During exposure to salt solution, chloride ions enter cracks and tend to diffuse into the cover concrete in the absence of an effective silane-based hydrophobic impregnation. As a consequence, the top rebar can become depassivated and start to corrode.

Initially, the ponding was performed for 19 cycles with a 3.0% by mass sodium chloride solution on the basis of a 2-week wet, 2-week dry ponding cycle procedure. Beginning with the 20th cycle, the sodium chloride concentration of the ponding solution was increased to 5.0% by mass in order to further accelerate the CCBCT, thereby achieving even harsher test conditions.

2.9 ELECTROCHEMICAL MEASUREMENTS

2.9.1 CORROSION POTENTIAL

The half-cell potential or open circuit potential is an indicator of the top rebar's electrochemical tendency to corrode. The potential is measured in the middle of the ponding cycle between the top rebar and a silver/silver chloride reference electrode immersed into the dike filled with sodium chloride solution. It's important to note that this corrosion potential data gives no direct indication on the amount of corrosion taking place, or the exact location of the corrosion.

According to the standard ASTM C876-09 'Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete'[3], rebar corrosion potentials of -200 and -350 mV, measured against a copper/copper sulphate sat. electrode (CSE), represent the boundaries of possible corrosion. Rebar potential values more negative than -350 mV CSE indicate probable corrosion, whereas potential values less negative than -200 mV CSE indicate probable lack of corrosion. The corresponding values for the rebar potentials measured against a silver/silver chloride sat. electrode (SSE) are -80 mV SSE and -230 mV SSE.

2.9.2 CORROSION CURRENT

The corrosion current is a direct indicator of the amount of corrosion taking place, and as such, is a direct indicator of the magnitude of metal loss in the corroding rebar. The corrosion current is calculated using Ohm's Law, $U = I \times R$, after measuring the corrosion-induced voltage across a high-grade 10-ohm resistor connecting the presumed anodic and cathodic rebars.

There is a good correlation between measured corrosion currents and the amount of deterioration observed in the post-testing visual inspection of cracked concrete beam test specimens. It must be noted, however, that corrosion currents determined during the test period represent only a portion of the total corrosion taking place, as small micro-corrosion cells involving anodic and cathodic areas on the top rebar will not be measured by this technique. This may be especially important for cracked concrete beams, as only a small portion of the top rebar is directly exposed to sodium chloride solution.

2.9.3 INTEGRAL CORROSION CURRENT

The integral corrosion currents show performance trends of the corrosion-inhibiting effect of the tested hydrophobic impregnating agents and the cumulative differences in the corrosion currents of different test specimens. This directly reflects the total amount of corrosion which has taken place, i.e. the total metal loss due to rebar corrosion. The integral corrosion current values were computed as the areas under the corrosion current vs. time diagram.

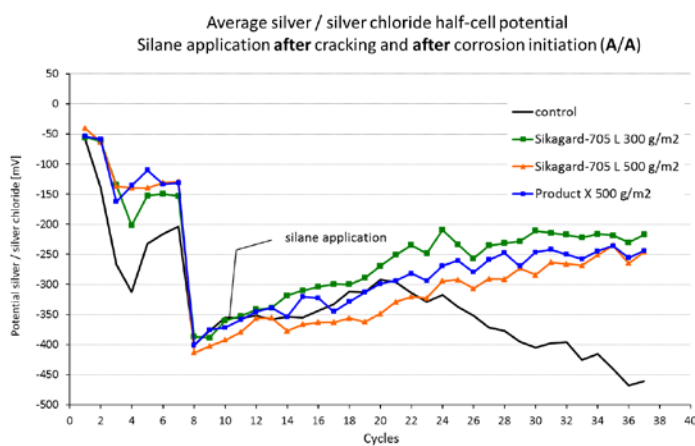
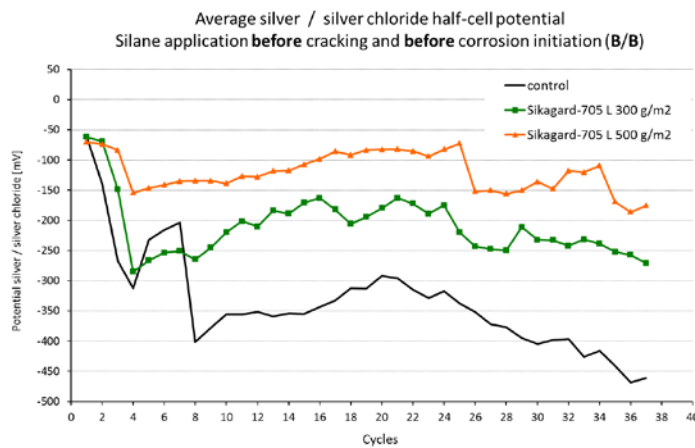
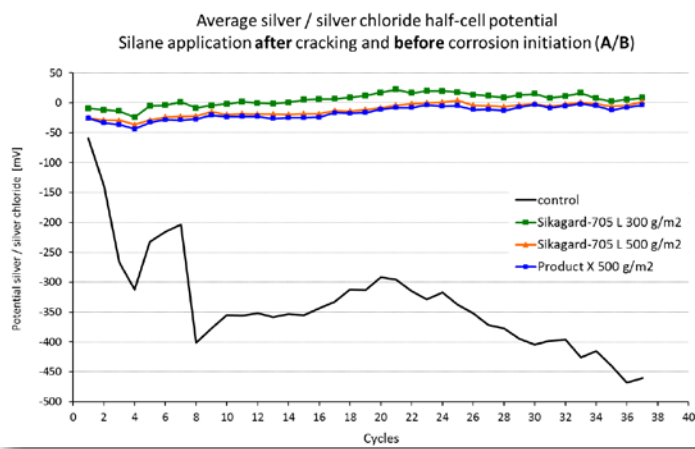
This way of integration assumes linear corrosion currents between consecutive measurements. It doesn't take into account the change in the corrosion current of specimens during the wet-dry cycling, but allows an easy comparison of the cumulative performance of different test samples

2.10 DURATION

The total duration of the corrosion testing lasted 37 wet/dry cycles or 1022 days (~2 years and 10 months)

3 RESULTS

3.1 HALF-CELL POTENTIAL

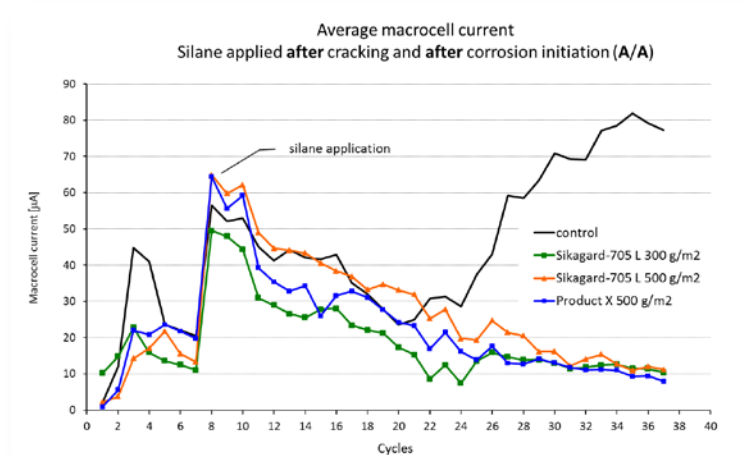
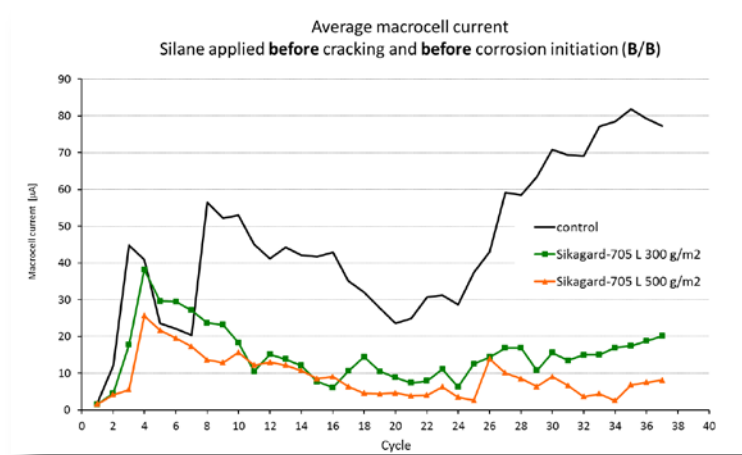
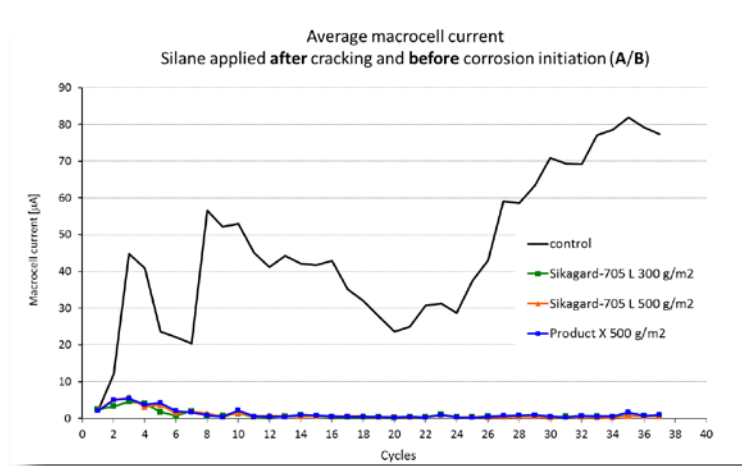


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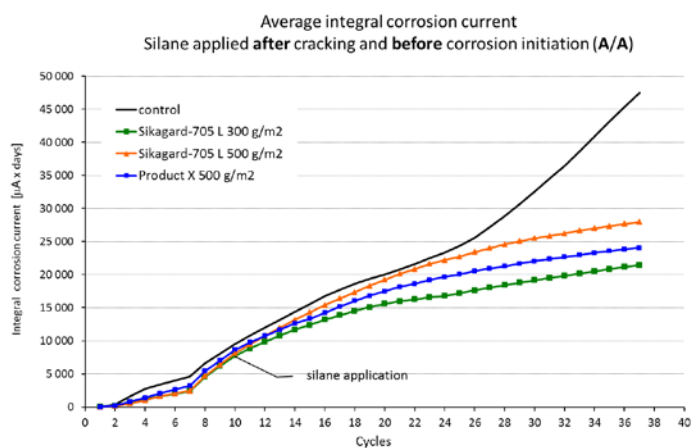
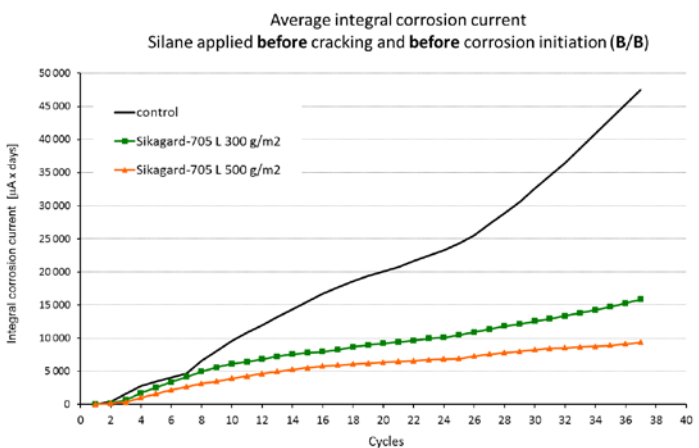
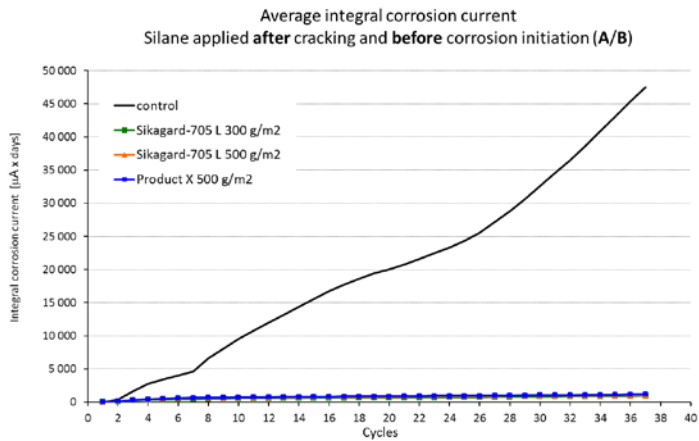
3.2 CORROSION CURRENT



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3.3 INTEGRAL CORROSION CURRENT



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3.4 ELECTROCHEMICAL PARAMETERS AT THE END OF THE CYCLES

Test	Application mode of treatment	Half-cell potential		Macrocell Current		Integrated Current	
		In mV	% of control	in μA	% of control	in μA	% of control
Control		-461.2		77.3		47 510	
SG-705 L-300	A/B	+8.4	-102%	0.6	-99%	930	-98%
SG-705 L-500		+1.6	-100%	0.5	-99%	1 029	-98%
Product X-500		-3.8	-99%	1.0	-99%	1 187	-98%
SG-705 L-300	B/B	-270.9	-41%	20.2	-74%	15 824	-67%
SG-705 L-500		-174.8	-62%	8.2	-89%	9 357	-80%
SG-705 L-300	A/A	-217.4	-53%	10.4	-87%	21 447	-50%
SG-705 L-500		-246.1	-47%	11.2	-86%	27 965	-41%
Product X-500		-244.2	-47%	8.0	-90%	24 030	-49%

3.5 RESULTS OF VISUAL EXAMINATION

Test	Application mode of treatment	Corroded Area		Remarks
		in cm^2	In % of control	
Control		25.2		Medium to heavy corrosion pitting, loss of rib definition
SG-705 L-300	A/B	0	-100%	No corrosion
SG-705 L-500		0	-100%	No corrosion
Product X-500		0.75	-97%	Light to no corrosion
SG-705 L-300	B/B	9.9	-61%	Medium to heavy corrosion pitting
SG-705 L-500		6.75	-73%	Light to medium corrosion pitting
SG-705 L-300	A/A	17.0	-33%	Medium to heavy corrosion pitting, loss of rib definition
SG-705 L-500		20.6	-18%	
Product X-500		13.85	-45%	

4 DISCUSSION

4.1 HALF-CELL POTENTIAL

According to ASTM C876-09 the potential values of -200 and -350 mV Cu / CuSO₄ (CSE) sat. represent boundaries of possible corrosion, with values more negative than -350 mV vs. CSE sat. indicating probable corrosion and values less negative than -200 mV CSE sat indicating probable lack of corrosion.

Converted boundary values for measurements against an Ag / AgCl KCl sat. half-cell (SSE) as reference electrode: -80 mV SSE and -230 mV SSE.

4.1.1 APPLICATION MODE A/B

Hydrophobic impregnation applied directly on the cracked concrete and prior to the onset of corrosion.

The graph clearly shows that regardless of the consumption rate (300 or 500 g/m²) or the product used (Sikagard-705 L or Product X), the steel reinforcement bars remain in a full passive environment with no risk of corrosion.

This is clearly shown in the graph but as well in the reduction of the potential versus the control and by the visual examination of the reinforcement steel bars at the end of the cycles.

4.1.2 APPLICATION MODE B/B

Hydrophobic impregnation applied before the formation of the cracks in concrete, but prior to the onset of corrosion.

The graph clearly shows that the hydrophobic impregnation tested still maintains a significant reduction of the potential. In addition it is obvious the influence of the consumption – higher rate of application yields to an higher reduction of the corrosion (seen in the graph and in the visual examination at the end of the cycles).

This finding confirms the results of some independent studies[4][5] that links the performances of hydrophobic treatment in presence of cracks to the ability of the product to migrate into the concrete.

4.1.3 APPLICATION MODE A/A

Hydrophobic impregnation applied directly on the cracked concrete, but after the corrosion has progressed significantly.

The graph shows an increase of the potential toward more passive conditions. This is also reflected in the electrochemical measurement at the end of the cycles comparatively to the control specimens. The visual examination is less significant as at when the products were applied, corrosion was already advanced and obviously this treatment does not reverse the process.

4.2 CORROSION CURRENT

The corrosion currents are not related to the area of the rebar, as the corroding areas of the reinforcing steel bars were unknown and dependent on the visual inspection at the conclusion of the testing. In addition the corrosion of rebars in the present investigation was mainly pitting corrosion and it is difficult to correlate it with parameters which are relevant for uniform (general) corrosion.

4.2.1 APPLICATION MODE A/B

Hydrophobic impregnation applied directly on the cracked concrete and prior to the onset of corrosion.

The graph clearly shows that regardless of the consumption rate (300 or 500 g/m²) or the product used (Sikagard-705 L or Product X), corrosion activity remains close to nil as these products prevent effectively the chloride to migrate within the cracks.

This is also confirmed by the visual examination at the end of the study where the reinforcing steel did not show any sign of pitting or corrosion except some corrosion traces in one of the beams where Product X was applied.

4.2.2 APPLICATION MODE B/B

Hydrophobic impregnation applied before the formation of the cracks in concrete, but prior to the onset of corrosion.

The graph clearly shows the same trend as for the Half-Cell potential graph highlighting the importance of penetration depth of the hydrophobic impregnation.

4.2.3 APPLICATION MODE A/A

Hydrophobic impregnation applied directly on the cracked concrete, but after the corrosion has progressed significantly.

The graph shows a tendency to reduce the corrosion regardless of the consumption rate (300 or 500 g/m²) or the product used (Sikagard-705 L or Product X).

This significant reduction of the macrocell current flow (~85 to 90%) could be explained by the reduction of water penetration due to the protection induced by the silane treatment and by drying of the concrete surrounding the reinforcing steel. This behaviour has been described by E.R. Giannini[6] to explain the reduction of alkali silica reaction when the concrete is being treated by silane products.

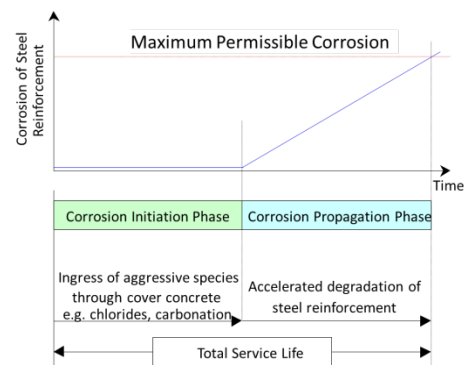
4.3 INTEGRAL CORROSION CURRENT

The values were computed as the area of the bar graphs under the corrosion current vs. time diagram. This integration assumes a linear corrosion current between consecutive wet cycles. It does not take into account any changes in the corrosion currents of the specimens during the wet and the dry cycles, but allows an easier comparison of the cumulative performance of different hydrophobic impregnating agents and consumptions.

4.3.1 APPLICATION MODE A/B

Hydrophobic impregnation applied directly on the cracked concrete and prior to the onset of corrosion.

The graph clearly shows that regardless of the consumption rate (300 or 500 g/m²) or the product used, the concrete specimens are still in the corrosion initiation phase while the non-treated specimens are in the corrosion propagation phase as described by Tuutti [7].



Simplified model of 2-stage corrosion process for steel reinforced concrete structures (after Tuutti)

4.3.2 APPLICATION MODE B/B

Hydrophobic impregnation applied before the formation of the cracks in concrete, but prior to the onset of corrosion.

The graph clearly shows the corrosion has started in the treated specimens, but the slope of the corrosion is much lower than the one of the control and also that it is dependent on the consumption used.

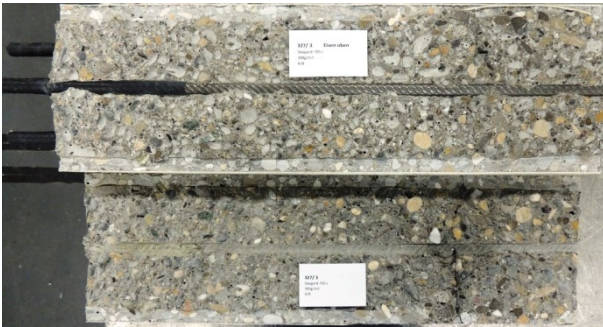
4.3.3 APPLICATION MODE A/A

Hydrophobic impregnation applied directly on the cracked concrete, but after the corrosion has progressed significantly.

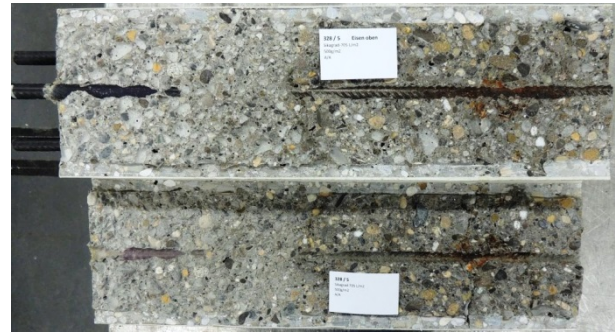
The same trend of corrosion reduction is observed for the three treated specimens.

4.4 VISUAL EXAMINATION

The visual examination of the different specimens confirms the trends and results provided by the electrochemical measurements.



No sign of corrosion in specimen treated by Sikagard-705 L applied **AFTER** cracking & **BEFORE** corrosion has initiated



Steel bar with sign of corrosion when treatment is applied after the corrosion has initiated

5 CONCLUSIONS

According to the results of this study the following conclusions can be summarized:

- Silane hydrophobic impregnation treatments are very effective to prevent the start of corrosion due to chloride ingress, even in the presence of cracks.
- The efficiency of the treatment is higher when the silane is applied directly on the cracked concrete.
- When the treatment is applied before the generation of cracks, the efficiency will depend on how deep the product has penetrated the concrete.
- When corrosion is already present, the treatment reduces the corrosion.
- No significant difference is found between Sikagard-705 L and the Product X tested; both performed similarly.

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7 LEGAL NOTE

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