Sika® FerroGard® corrosion inhibitors for protection of reinforced concrete structures

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A corrosive environment (chlorides), carbonation of the concrete cover, poor workmanship in construction and other factors can lead quite quickly to corrosion of the reinforcing steel. As a result many exposed structures cannot achieve their original design life unless additional repair work is carried out. This means that a large number of bridges and other structures around the world have to be repaired due to reinforcement steel corrosion. There are a number of corrosion protection systems on the market with varying cost/performance ratios. Sika modified amino alcohol based corrosion inhibitor systems are described below, which can be used as concrete admixtures, corrosion inhibiting impregnations for existing concrete structures or as additives in concrete repair mortars. They are also environmentally friendly, easy to use and economic. Therefore as a system component, these often represent a viable option for the maintenance and protection of concrete structures, or a cost effective alternative to traditional repairs and other electrochemical methods for the refurbishment of concrete structures.

1. Corrosion inhibitors

The technology and use of corrosion inhibitors is now widespread and well accepted worldwide. They are materials which when used in small quantities, are able to delay the onset of corrosion in metals such as reinforcement steel and to reduce the corrosion rate where corrosion already exists. Corrosion inhibitors can be classified in three main groups: Anodic, cathodic and mixed inhibitors. Anodic and cathodic corrosion inhibitors act respectively on the anodic areas of the reinforcing steel (reacting with corrosion products to form a passive film), or on the cathodic areas (acting as an oxygen barrier). Passivating inhibitors such as nitrites are a particular type of anodic corrosion inhibitor. The inhibiting effect they achieve is normally very good, provided sufficient quantities are present. Mixed corrosion inhibitors influence both the anodic and the cathodic partial reactions of the corrosion process, by forming a protective monomolecular barrier film on the steel surface.
The Sika corrosion inhibitors described below are based on aqueous solutions of partly neutralised amino alcohols and belong to the mixed corrosion inhibitor group. The film formed on the steel surface by the adsorbed amino alcohol also acts as a barrier against chlorides which penetrate the concrete, provided the chloride concentration directly adjacent to the steel surface does not exceed a specific threshold level. The addition of these corrosion inhibitors to concrete therefore effectively raises the chloride concentration threshold necessary for the onset of corrosion and also reduces the reinforcement corrosion rate, after any corrosion has eventually set in.

2. Sika® FerroGard®: Globally tested corrosion protection system for reinforced concrete

In order to be a suitable system component for the repair of corroded reinforced concrete, or the preventive protection of existing structures, a corrosion inhibitor must meet several important criteria: It should be able to delay the onset of corrosion, reduce the corrosion rate or even repassivate the steel surface. It should be simple and easy to use and preferably environmentally friendly, penetrate the concrete quickly and deeply enough and also leave no visible traces on the concrete surfaces.

Sika provides two different types of corrosion inhibitor for use on reinforced concrete: Corrosion inhibitors of the concrete admixture type (Sika FerroGard-901), which are added to the concrete during its production, or are used as corrosion inhibiting components of repair mortars; plus surface applied corrosion inhibiting impregnations (such as Sika FerroGard-903). When applied in hardened concrete, these can penetrate the concrete matrix to protect the steel reinforcement from corrosion and/or reduce the corrosion rate of the steel. Surface applied corrosion inhibitors have the great advantage that they can be post applied on existing hardened concrete structures when required.

The interaction between inhibitors and steel was investigated at Heidelberg University (M. Grunze et al.) and by Brundle & Associates, San Jose (USA) by X-ray photoelectron spectroscopy (XPS) [1]. Secondary ion mass spectroscopy (SIMS) provided data to identify the molecules of the surface film that is formed. The results show that amino alcohols form a monomolecular film on the steel and that they can displace chloride ions and also other aggressive ions from the surface.

Penetration of Sika FerroGard in hardened concrete

The penetration of Sika FerroGard into hardened concrete was investigated by Sika using amino alcohol depth profile analysis in core samples. Slices corresponding to different concrete depths were cut from concrete cores and crushed, then the amino alcohol present in the individual depth samples was extracted and analysed quantitatively using ionic chromatography.
Alongside this quantitative laboratory method, a qualitative method which is suitable for use on construction sites in obtaining an approximate estimate of the amino alcohol content was also developed. With the help of this Sika test kit, it is possible to check directly on site how far surface applied Sika FerroGard has penetrated into the concrete structure and whether the penetrating corrosion inhibitor has already reached the level of the reinforcement.

Corrosion tests

Electrochemical testing and measurements were taken by Sika Germany in Stuttgart. Potentiodynamic polarisation measurements were taken on reinforcement samples in potassium hydroxide solutions containing chloride ions, with and without added corrosion inhibitor (Fig. 1).

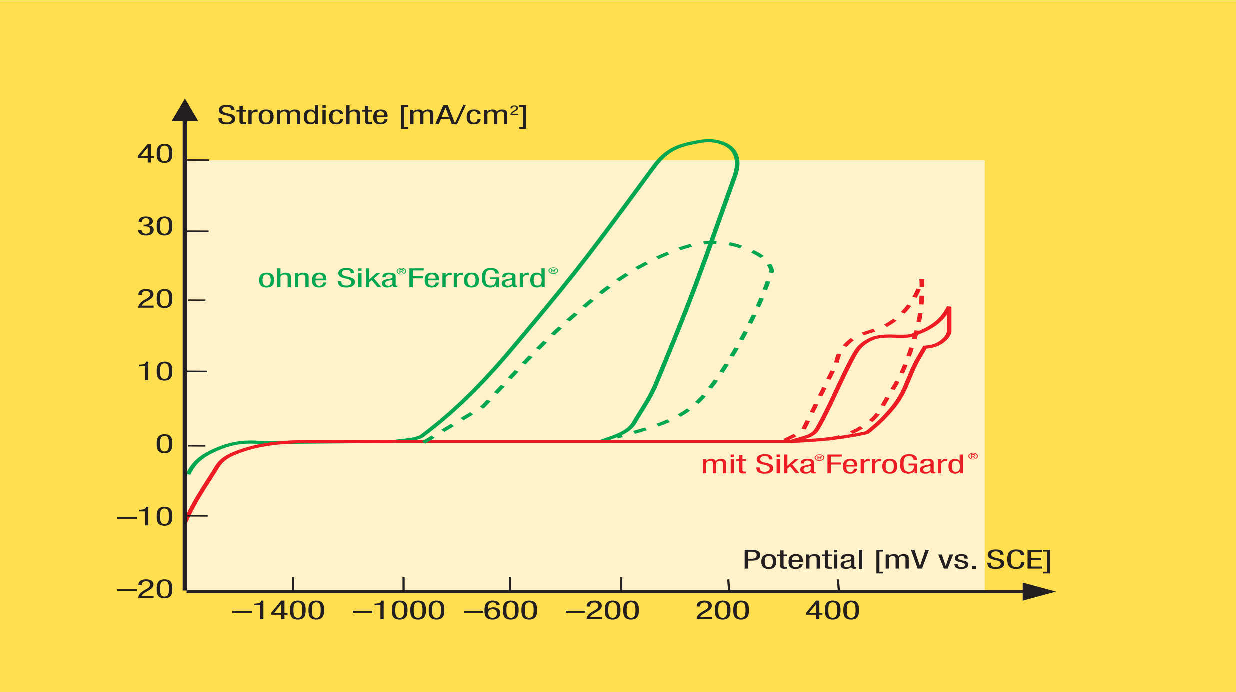

Fig. 1 Potentiodynamic polarisation on mild steel in alkaline solutions containing chloride ions

Sika Technology AG performed electrochemical measurements to test the corrosion protection effect of Sika FerroGard-901 on cracked concrete beams under cyclic stress from a sodium chloride solution. This provided an analysis of the effectiveness of inhibitors in protecting the embedded steel from corrosion in cracked concrete exposed to chloride penetration. The test configuration simulated a cracked bridge deck in which the top layer of reinforcement was exposed to attack from de-icing salts, both directly through a 0.25 mm wide crack formed artificially and indirectly by the diffusion of chloride ions into the concrete (Fig. 2).

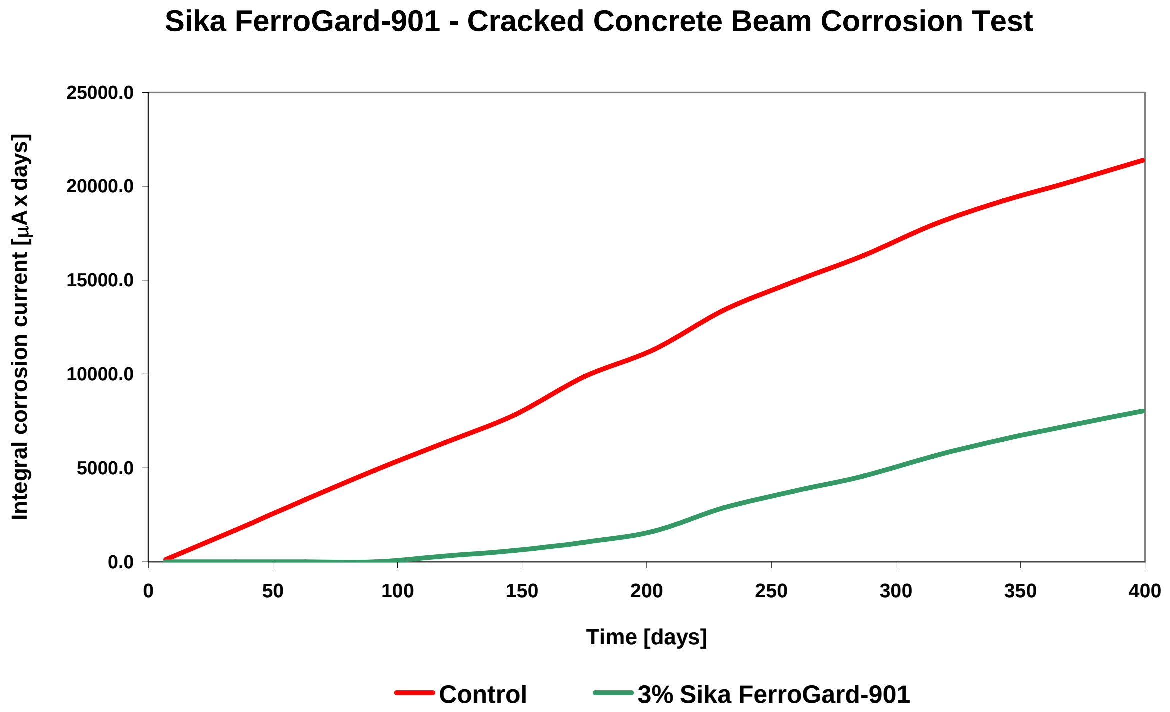

Fig. 2 Cracked concrete beam corrosion test: Integral corrosion current vs. time

Other corrosion tests were conducted at different universities and test institutes.

F. Bolzoni et al. [2] carried out corrosion tests with the corrosion inhibitor Sika FerroGard-901 on reinforced concrete samples in presence of chlorides at the Politecnico di Milano (Italy). They demonstrated that at a dosage of 10 litres/m^3 of concrete, its corrosion protection effect was good up to a chloride content of 1.2% of cement weight and negligible corrosion rates resulted.

G. Batis and Th. Routoulas [3] tested Sika FerroGard-901 on concrete samples immersed in sea water at the National Technical University of Athens (Greece). The results showed that at the tested dosage of 3.0% Sika FerroGard-901 (of cement weight), the product has a good corrosion protection effect similar to that of a calcium nitrite based corrosion inhibitor tested at the same time.

M. Mulheron [4] carried out tests with Sika FerroGard-903 on pre-corroded reinforced concrete slabs of different concrete grades at the University of Surrey (UK). The results of the corrosion measurements demonstrated the corrosion inhibiting effect of the surface applied impregnation Sika FerroGard-903. As expected, the corrosion inhibitor penetrated more quickly into concrete slabs with 28 day compressive strength of 29.7 MPa and reduced the corrosion rate faster (Fig. 3) than when applied on 75.4 MPa concrete slabs (Fig. 4). However, by the end of the test period of approximately 7 weeks, almost equivalently reduced, low corrosion rates were measured on both grades of concrete.

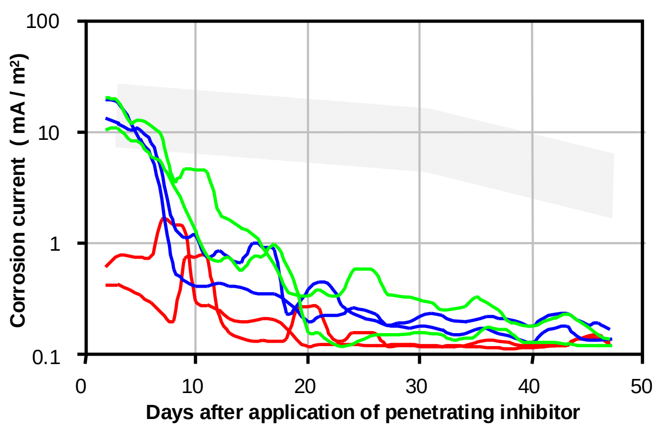

Fig. 3 and Fig. 4: Specimens treated with Sika FerroGard-903: Curves for 10 mm concrete coverage are shown in green, for 20 mm in blue and for 40 mm in red.
Control samples: Range of measured corrosion currents for 10, 20 and 40 mm concrete cover shown as hatched area.

Fig. 3: 29.7 MPa concrete: Change in corrosion current with time after application of Sika FerroGard-903

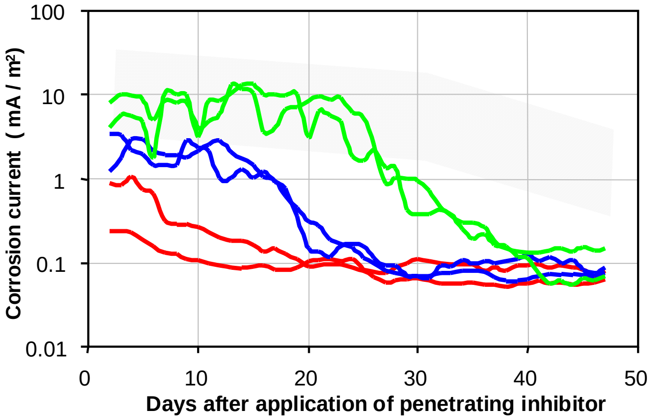

Fig. 4: 75.4 MPa concrete: Change in corrosion current with time after application of Sika FerroGard-903

J.R. Morlidge [5] tested the corrosion inhibiting effect of Sika FerroGard-903 at the Building Research Establishment (BRE), Garston, Watford (UK), by its preventive application on 150 mm concrete cubes containing non-corroded steel reinforcement. To initiate corrosion, the specimens impregnated with 1000 g/m^2 corrosion inhibitor were exposed to cyclic stress from a 1% chloride solution. The corrosion advance was determined by measuring the linear polarisation of the reinforcement steel. Initially, up to a test duration of around 250 days, the corrosion current density of all the samples fluctuated within the lower density range. From that time the control samples began to corrode significantly, whilst the corrosion current density of the samples treated with corrosion inhibitor remained at a low level throughout the 960 day test duration (Fig. 5).

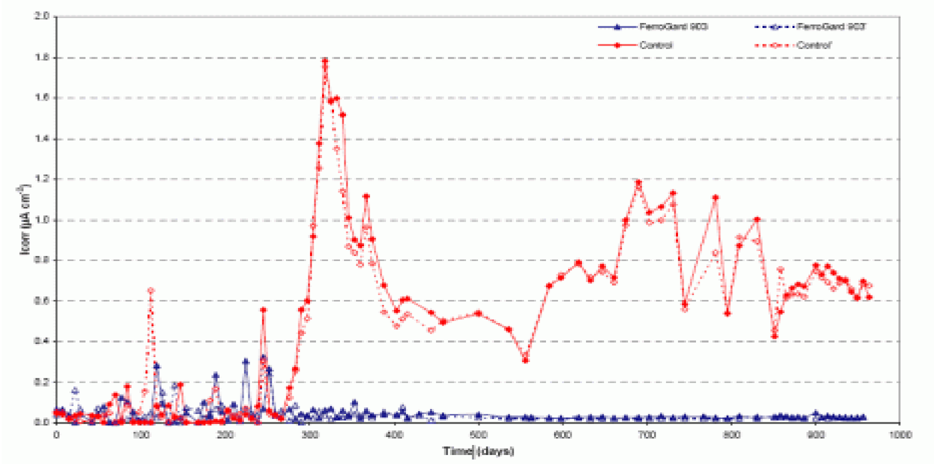

Fig. 5: Change in measured corrosion current density (I_{corr}.) for Sika FerroGard-903 treated and control concrete specimens exposed to an accelerated chloride ponding procedure.

R. Heiyantuduwa and M.C. Alexander [6] of the University of Cape Town, South Africa, found that the corrosion inhibitor Sika FerroGard-903 considerably reduced the corrosion rate on reinforcement steel corroded due to carbonation, whether the corrosion inhibitor was applied before or after initiation of the corrosion by carbonation, on the surfaces of the 30 MPa concrete specimens used for the tests.

As part of the 3 year EU research project SAMARIS (Sustainable and Advanced Materials for Road Infrastructure) [8], the surface applied corrosion inhibitor Sika FerroGard-903 underwent extensive laboratory and field tests. The key questions and main focus of interest was: Within what application limits and under what conditions, a good corrosion inhibiting effect can be achieved using Sika FerroGard-903 and with what limitations and application conditions, the use of the product can and cannot be recommended. The project also examined whether application of the corrosion inhibitor affected the concrete properties. In addition to laboratory tests, corrosion measurements were taken over long periods on various bridges and buildings that have been treated with Sika FerroGard-903.

3. Discussion of test results

Effect of the inhibitors on the properties of fresh and hardened concrete

When inhibitors were used, with or without other admixtures such as concrete plasticizers, similar compressive strength levels were obtained. The setting times and compressive strengths after 7 and 28 days were not generally affected by adding the quantities of 2-4% inhibitor (by weight of cement) The air quantities in the fresh concrete can still be increased by air entrainers and the air void configuration is not fundamentally changed. There were no adverse effects on the concrete properties or quality due to the addition of Sika FerroGard, neither in the fresh nor in the hardened concrete.

Initial transport mechanism into concrete and mortars

Sika modified amino alcohol based corrosion inhibitors were found to penetrate the concrete matrix irrespective of the position and plane of the application area (overhead, vertical, above). Capillary suction in the concrete is the main transport mechanism. The transport rate of the corrosion inhibitor can therefore be expected to be high if the concrete cover moisture content is low, it therefore also becomes lower with a higher concrete moisture content and is very low with a water saturated concrete surface. The initial transport rate depends mainly on the porosity and therefore the density of the concrete matrix and the moisture content.

Interaction between corrosion inhibitor and steel surface

Investigations showed that the single amino alcohol N,N-Dimethylethanolamine used as the test control sample forms a protective film about 20 Å thick on steel surfaces. With Sika FerroGard this film thickness can be up to 1000 Å. Measurements by X-ray photoelectron spectroscopy (XPS) revealed that hydroxyl groups and also anions such as chloride ions which normally have a strong bond with the steel surface, can be displaced and replaced by these Sika FerroGard amino alcohol molecules. This allows re-passivation of steel in a low chloride containing environment. The formation of complex compounds with ferrous ions on the steel surface by chemisorption was clearly demonstrated. As a result Sika FerroGard is then very hard to remove from steel surfaces, for example by the action of water.

Corrosion tests on cracked beams

As anticipated the results show that the reinforcement in all of the test beams corroded during the test period with the very severe test conditions selected. However, it was clear that the specimens containing the corrosion inhibitor performed very much better than the control samples. Sika FerroGard resulted in delayed onset of corrosion and also reduced the rate of corrosion by more than half, which ultimately means in practice that the service life of a concrete structure treated with Sika FerroGard corrosion inhibitor can be more than doubled (Fig. 6).

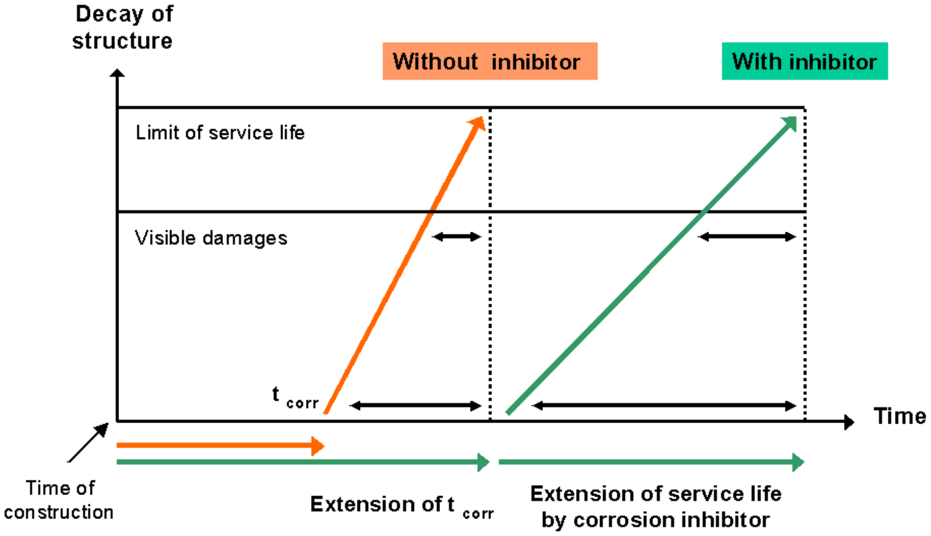

Fig. 6 Extension of service life of steel reinforced concrete structures by corrosion inhibitors

Chloride concentration in concrete near reinforcement

One of the most important findings obtained under the SAMARIS project in connection with surface applied corrosion inhibitors, concerns their effectiveness as a function of both the chloride concentration and the inhibitor concentration, and directly adjacent to the reinforcement. Concentrations of up to 0.5% free chloride ions (based on cement weight) around the reinforcement and yet still maintaining low to average corrosion rate of less than 0.5 $\mu A/cm^2$ represents the best case scenario. With average chloride contents of up to 1% free chloride ions immediately adjacent to the reinforcement, surface applied Sika FerroGard-903 also still shows good results, provided that a sufficient inhibitor/chloride concentration ratio is obtained. With chloride contents of around 1-2% free chloride, additional protective measures such as barrier coatings or other electrochemical means are normally necessary. If feasible, an increase in the quantity of corrosion inhibitor applied could also be considered. With very high chloride contents of over 2% free chloride ions at the depth of the steel reinforcement, the use of surface applied corrosion inhibitors would usually not be recommended.

Successful use of surface applied corrosion inhibitors such as Sika FerroGard-903 therefore depends to a large extent on whether the products are used within their application limits. The same conclusion was reached by K. Nairn et al [7] of Monash University, Clayton (AU) in a review of the existing literature on amino alcohol based corrosion inhibitors for reinforced concrete carried out in 2003 as part of their research into corrosion protection.

4. Overall Conclusions

The corrosion inhibiting effect of Sika amino alcohol based inhibitors has been proven by tests in solution and concrete samples and by the measurement of the corrosion rates in structures. Corrosion measurements taken on concrete specimens have shown that these inhibitors delay the onset of corrosion and can slow down the corrosion rate considerably. Their transport in the concrete and their interaction with the reinforcement steel is explained and has been described in several scientific publications. The Sika FerroGard products formulated on the basis of these corrosion inhibitors can be used both as a concrete admixture and on existing reinforced concrete structures in the form of a surface applied, corrosion inhibiting impregnation. This impregnation can be applied to the cleaned surface of a structure by brush, low pressure spray or rollers (Fig. 7). With the use of Sika FerroGard surface applied corrosion inhibitors, the amount of concrete broken out and the removal of sound concrete during repairs due to corroded reinforcement in concrete structures, can be greatly reduced in many cases.

Fig. 7 Application of Sika FerroGard-903 by low-pressure spray

The use of corrosion inhibitors therefore can help to extend the service life of structures by delaying the time to the onset of corrosion and/or by reducing the corrosion rate after the onset of corrosion (Fig. 7). It should be stated that once corrosion has already started, inhibitors can only stop corrosion completely if the corrosion rates are low. The sooner after the onset of corrosion a corrosion inhibitor can be applied, the more effective it is, this is because the protective film which it forms is most effective on a steel surface which is only slightly corroded. The period after loss of passivation and shortly before the onset of corrosion, is actually the ideal time for application as a component of a preventive maintenance strategy. Sika FerroGard corrosion inhibitors can therefore represent a very easily and quickly applied, cost effective component of maintenance and repair strategies for concrete bridges and other reinforced concrete structures..

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