STATYBINĖS KONSTRUKCIJOS IR TECHNOLOGIJOS
ENGINEERING STRUCTURES AND TECHNOLOGIES
2009
1(4): 183–194

Lietuvos statybininkų asociacija

doi: 10.3846/skt.2009.22

# A TEST OF REINFORCEMENT CORROSION PROGRESS IN THE PRESENCE OF ORGANIC CORROSION INHIBITORS

**Andrzej Śliwka, Adam Zybura**

*Faculty of Civil Engineering, The Silesian University of Technology,*
*ul. Akademicka 5, 44-100 Gliwice, Poland*
*E-mail: andrzej.sliwka@polsl.pl, adam.zybura@polsl.pl*

*Received 10 09 2009; accepted 23 11 2009*

**Abstract.** Test results for KCR and DME migrating inhibitor efficiency are presented. The method of linear polarization is used in the tests on loaded reinforced concrete elements. Various durations of inhibitor activity, cracked concrete cover and different levels of reinforcement corrosion development in test parts are taken into account. The inhibitors are only partly efficient at low levels of corrosion development at an early stage, however, after two years the protective work is not verifiable. In the case of intense reinforcement corrosion a reduction in its degree is not observed, even directly after inhibitors have been applied.

**Keywords:** concrete, inhibitor, corrosion, efficiency, protection, reinforcement, reinforced concrete.

## 1. Introduction

The durability of reinforced concrete structures is limited as a result of the occurrence of reinforcement corrosion. The most common cause of reinforcement corrosion is concrete carbonation and chloride ion activity. The corrosion threat is increased by cracks, which make penetration deep into the concrete cover easy for aggressive ions (Falewicz *et al.* 2005). The protection of reinforced concrete structures from environmental influences and the extension of their operational life is nowadays one of the most important maintenance problems.

At the first stage of reinforcement bar corrosion, when the concrete cover is still intact, the alternative to traditional repairs is protection of the reinforcement by migrating inhibitors. Migrating inhibitors are compounds, which by penetrating the concrete cover should reduce the speed of the reinforcing steel corrosion, and even stop completely the destructive processes. Due to low costs and ease of use, migrating inhibitor protection seems to be a very attractive way of extending the operational life of reinforced concrete structures.

However, even if migrating inhibitors are used and recommended for reinforced concrete structure maintenance, there is no certainty that in all conditions and over long periods of operation they will adequately protect the structure from corrosion. Such fears arise mainly from scale difference, in which tests are made, which are foundations for conclusions about performance of steel reinforcement in real structures. Moreover there are difficulties in imitating in the laboratory real conditions of reinforcement interaction with concrete cover. Uncertainty is created also by producers' fairly liberal requirements concerning inhibitor application, independently of complicated reinforcement corrosion mechanisms caused by varied environmental influences and unstable humidity.

Most often the effectiveness of concrete reinforcement inhibitor protection is estimated in a solution modelling the pore liquid using polarization methods (Alonso *et al.* 1996; Jamil *et al.* 2005; Mammoliti *et al.* 1999; Phanasgaonkar *et al.* 1997). In more advanced tests reinforced concrete elements from a few centimetres to several tens of centimetres are used (Gaidis 2004; Montes *et al.* 2004; Morris, Vazquez 2002; Holloway *et al.* 2004).

The results obtained in such tests are transferred to real structures, whose dimensions exceed greatly the test elements. Thus, assurance of effective inhibitor protection of structures in real conditions is difficult and may not be entirely reliable, because along the reinforcement length there occur varied concrete influences resulting from irregular distribution of humidity, concentration of aggressive ions – for example, chlorides – and also rapid changes caused by newly occurring cracks in the concrete cover (Kondratova *et al.* 2003). An influence on the effectiveness of the protection may also be determined by the factor causing the corrosion, the extent of the electrochemical process development as well as the moment of inhibitor application – before the appearance of corrosion or after its initiation (Alonso *et al.* 1996; Andrade *et al.* 1992; Ngala *et al.* 2002).

The purpose of the article is to present the test results of an organic inhibitor effectiveness in conditions similar to the ones taking place in reinforced concrete structures. In the tests the mechanical loads as well as cracks in concrete cover were taken into account. Reinforcement corrosion with low and high level development was induced by cyclic moistening with a sodium chloride solution.

For slowing down the reinforcement corrosion an individually developed organic migrating inhibitor was used, marked with the symbol KCR, with the DME compound being part of this inhibitor (Klakočar-Ciepacz, Falewicz 2003). Moreover for comparative purposes inhibitors manufactured by well known building chemical companies, recommended for the protection of reinforced concrete structures, were also used.

## 2. Choice of inhibitor – tests in model solutions

In the search for a substance which could be a migrating inhibitor in reinforced concrete structures tests on several organic compounds were done (Klakočar-Ciepacz, Falewicz 2003). For the tests there were chosen solutions characterized by favourable attributes in the conditions present in the porous structure of concrete. Among those considered were the appropriate energy of vapour, probable ease of diffusion in concrete, non-toxicity, etc. The following were accepted:

- synthesized in The Institute of Precision Mechanics in Warsaw, the compounds IFCHAN 1 and IFCHAN 100, using concentrations from 20 mg/dm$^3$ to 300 mg/dm$^3$,
- synthesized in The Academy of Science in Moscow, compounds IFCHAN 18 and IFCHAN 118, using concentrations from 20 mg/dm$^3$ to 250 mg/dm$^3$, as well as an inhibitor called DME, whose main component is the technical product of dimethylamineethanol compound – $(CH_3)_2NCH_2CH_2OH$, using concentrations from 50 mg/dm$^3$ to 500 mg/dm$^3$,
- an individually developed inhibitor mixture labelled with the symbol KCR related to the compound DME with the addition of a penetrating substance at a concentration of 0.1 ÷ 0.5% by volume (Klakočar-Ciepacz, Falewicz 2003).

Up to now, DME compound has been used as a steel corrosion inhibitor in industrial installations, in which alkaline solutions are present, but of different composition than concrete pore solution. Moreover, for comparative purposes there was used an inhibitor produced by a well-known building chemical company and recommended for reinforced concrete structure corrosion protection. This inhibitor was marked as the preparation M.

The tests were carried out in an electrolyser containing 3 types of solutions:

- a mixture of hydroxides 0.06 M KOH + 0.20 M NaOH + 0.001 M $Ca(OH)_2$ according to (Tullmin *et al.* 1995),
- the same mixture of hydroxides with the addition of 0.05 M NaCl and saturated with gaseous $CO_2$ to pH = 8.97,
- water extract from hardened cement paste with chloride admixture and carbonated – concentration of main ions [mg/dm$^3$]: $Ca^{2+}$ – 0.914; $K^+$ – 5360.0; $Na^+$ – 1500.0; $CO_3^{2+}$ – 3885.0; $Cl^-$ – 885.0; pH = 9.03.

Measures were taken using the potentiodynamic method according to the scheme shown in Fig. 1.

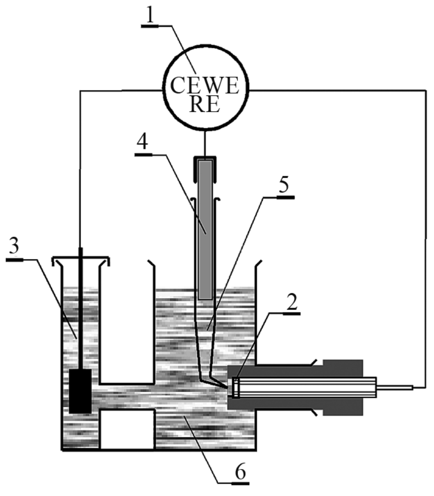

**Fig. 1.** Scheme of the measuring system: 1 – potentiostat, 2 – reinforcement steel working electrode, 3 – platinum counter electrode, 4 – calomel reference electrode, 5 – Łagin's capillary, 6 – liquid modelling concrete pore solution

Polarization curves were determined, with corrosion potential $E_{cor}$ and corrosion current density $i_{cor}$, on the basis of which the speed of corrosion and protection efficiency of each of the inhibitors was calculated

$$S = \frac{V_c - V_{c,inh}}{V_c} \cdot 100\%,$$

where: $V_c$ – corrosion speed in a solution without inhibitor, $V_{c,inh}$ – corrosion speed in a solution with inhibitor.

The highest efficiency was noticed by the highest concentrations of inhibitors. Fig. 2 shows basic results of the efficiency tests of the analysed inhibitors in model solutions submitted to carbonation and contaminated with chlorides. Complete results are presented in the papers (Klakočar-Ciepacz, Falewicz 2003; Klakočar-Ciepacz 2002).

The most promising results were obtained using the individually developed inhibitor labelled with the symbol KCR. The KCR inhibitor showed very high effectiveness. In a solution composed of a mixture of hydroxides its effectiveness exceeded 95% and was the highest of all the tested substances – Fig. 2a. In the same solution the DME compound showed lower effectiveness amounting to only 30%. In a water extract from hardened cement paste the effectiveness of the KCR inhibitor was lower and measured about 85% – Fig. 2b. The manufactured preparation M was characterized by lower effectiveness, equal to 60%. The remaining substances were characterized by even lower effectiveness, whereas one (IFCHAN 118) caused acceleration of corrosion processes.

The effect of KCR inhibitor at 0.5% concentration is characterized by polarization curves shown in Fig. 3.

In a non-carbonated and chloride free solution, i.e., a mixture of hydroxides (Fig. 3a), the KCR inhibitor worked properly, because it not only prevented a worsening of the protection properties, but even improved them. Use of the KCR inhibitor caused a repeated lowering of passive current density as well as complete protection from pitting corrosion. Puncturing of the passive layer and pit formation were not attained in all ranges of potential changes until 1.2 V was reached – the oxygen emission potential.

In the same solution the carbonated and chloride-containing KCR inhibitor significantly improved protection properties (Fig. 3b). A repeated lowering of corrosion current density and significant increase of pitting corrosion resistance also occurred – the potential of pit formation was moved about 400 mV in a positive direction.

In a carbonated and chloride-containing water extract derived from hardened cement paste the KCR inhibitor showed similar protection tendencies with intermediate results, as in the two discussed cases (Fig. 3c). Moving the corrosion potential in a positive direction, with simultaneous lowering of anode and cathode polarization curves and corrosion current density testified to the mixed character of the KCR inhibitor at work.

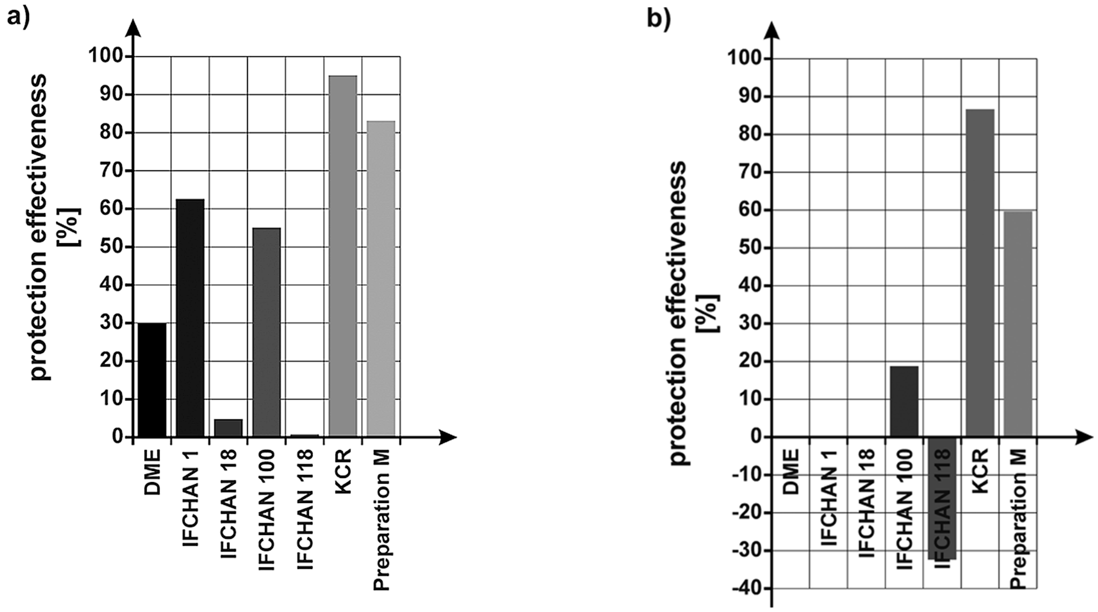

**Fig. 2.** Effectiveness of inhibitors in carbonated and chloride contaminated solution: a) mixture of NaOH, KOH and $Ca(OH)_2$ hydroxides, b) extract of hardened cement past

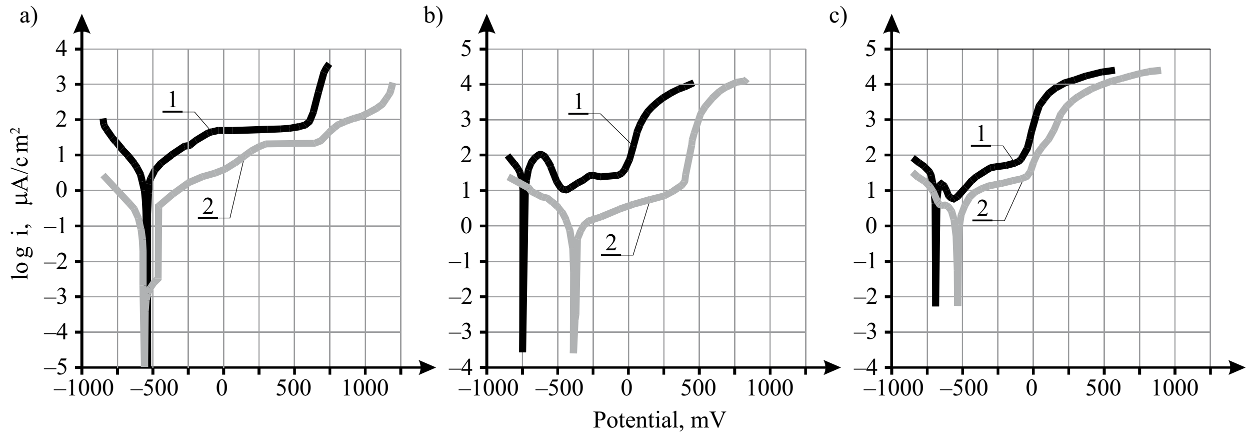

**Fig. 3.** Polarization curves of reinforcing steel in model solution:
1 – without inhibitor, 2 – with KCR inhibitor. Description in the text

Fig. 4 shows polarization curves obtained in the same model solutions under the influence of preparation M at 0.5% concentration by weight. Comparison of these curves with diagrams presented in previous figures indicates that the protection characteristics of the KCR inhibitor were better.

The tests carried out indicate that both the KCR mixture and its basic component DME, blocking anode and cathode reactions, belong to a mixed inhibitor group. In respect to it being the best, most highly effective substance KCR was chosen for further tests carried out on reinforced concrete samples. Part of these tests was also carried out using the basic component of this inhibitor – DME compound. It should be emphasised, that neither substance worsened the protection properties of non-carbonated and chloride free pore solution.

## 3. Range and methods of testing inhibitor effectiveness in concrete elements

Altogether thirteen concrete elements with the dimensions 50×100×600 mm were tested. Elements were tested in a loaded state and with no load participation. The loading system with test element is shown on Fig. 5. The elements contain a 6 mm ϕ steel reinforcement, St3S *1*, and a titanium wire *2* of 1.6 mm diameter covered with a 3 µm platinum layer, serving as the counter electrode. Titanium wires and reinforcement bars were supplied with corrosion insulators *3* protecting them from crevice formation.

Part of the elements were loaded with concentrated force after 28 days of curing by a device fitted with a mechanical force gauge *4* and spring regulators *5*. The load was increased to the moment when a crack of about 0.3 mm width developed in the stretch area.

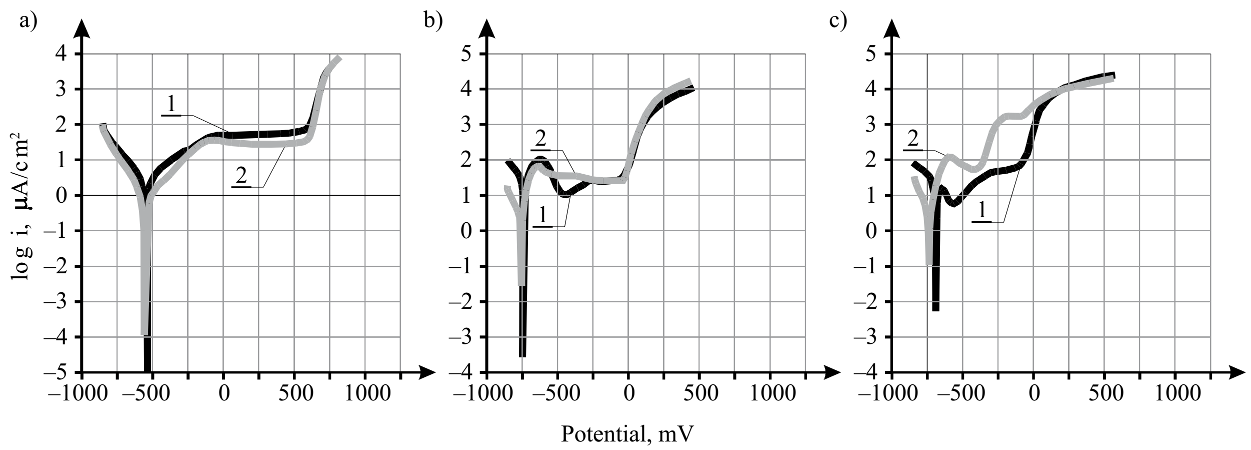

**Fig. 4.** Polarization curves of reinforcing steel in model solution:
1 – without inhibitor, 2 – with M preparation. Description in the text

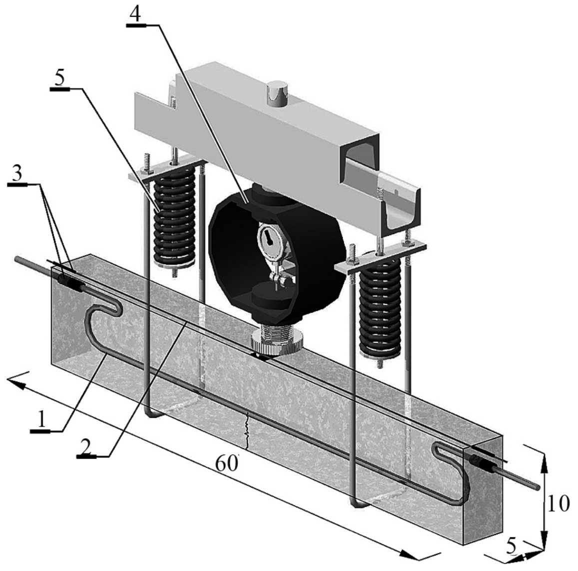

**Fig. 5.** Scheme of element structure and way of loading

The effectiveness of the inhibitor activity was determined on the basis of corrosion current density measurements. Measurements were performed by the polarization method in a three electrode system – Fig. 6. Potentiostat *1* is a computerised measurement device comprising electronic measuring card PC4/300 supplied by Gamry Instruments Inc., running a DC105 application for direct current tests. The potentiostat is connected to test element reinforcement *2* and Ag/AgCl reference electrode, with titanium wire *4* being counter electrode. Reference electrode *3* is placed in loaded elements in a crack and at a distance of 20 cm from the crack, on both sides of it, whereas in non-cracked elements, in the middle of the element length. Parallel arrangement of the titanium wire and reinforcement assure regular polarization of the entire tested electrode, which is a requirement for correct results in corrosion tests.

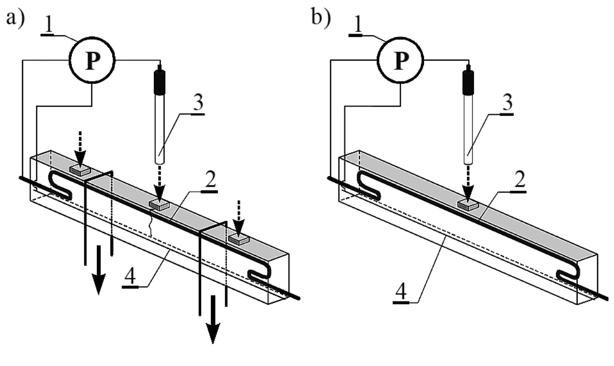

**Fig. 6.** Scheme of polarization measurements in the beams: a) loaded and cracked, b) unloaded. Description in the text

Before starting the measurements the corrosion potential was stabilized for about 60 minutes. Then according to the measurement program the reinforcement was polarized.

Tests were performed in two stages, in which the cyclic work of the chloride solution led to differentiated reinforcement corrosion intensity – Fig. 7.

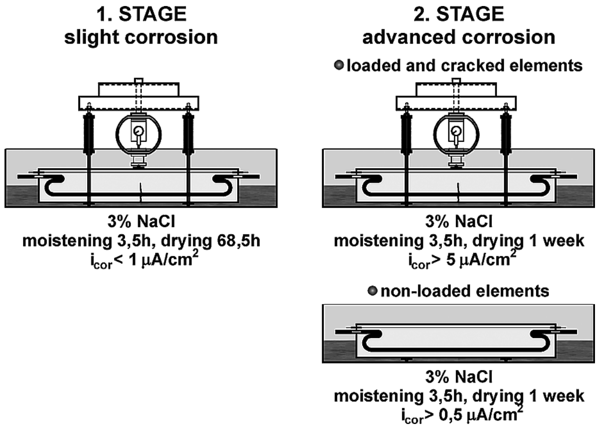

**Fig. 7.** Method of reinforcement corrosion initiation

In first stage tests were performed on loaded cracked elements of C12/15 concrete. Five elements (Nos. 1 ÷ 5) were moistened with NaCl solution for 3.5 hours, and then dried for 68.5 hours. Repeating cycles continuously until achieving a value of about $i_{cor} \approx 0.5$ μA/cm$^2$ in the corrosion current density control measurements in the crack gives evidence of the low degree of progress in reinforcement corrosion according to (Andrade, Alonso 1996).

In the second stage eight elements composed of C20/25 concrete were tested. Four elements were loaded and cracked (Nos. 6 ÷ 9), whereas 4 were left without load (Nos. 10 ÷ 13). These elements too were moistened with NaCl solution for 3.5 hours, but dried longer – in a one week cycle.

In cracked elements moistening with sodium chloride solution was repeated till there was a gain in control measurements much higher than earlier corrosion current density, higher than $i_{cor} > 5.0$ μA/cm$^2$ value.

In the non-loaded element cyclic moistening with sodium chloride solution lasted to the moment of the appearance of a corrosion current density value exceeding $i_{cor} > 0.5$ μA/cm$^2$.

After the onset of corrosion on the concrete cover surface an inhibitor was applied. The inhibitor was applied analogously, as in reinforced concrete structures in service, by covering the reinforcement concrete cover surface. The concrete surface was repeatedly covered with two or three layers of solution, paying attention to complete absorption of every layer by the pores.

## 4. Stages and results of tests for low level reinforcement corrosion development

In the first stage tests were carried out in two parts, the course of which is shown graphically in Fig. 8.

The surface of element No. 1 was covered with DME compound, being the basic component of KCR inhibitor, in the proportion 3 g/dm$^2$. On elements Nos. 2 and 3 KCR inhibitor was used in two different quantities – 3 g/dm$^2$ and 6 g/dm$^2$. Moreover elements Nos. 4 and 5 were protected with two migrating inhibitors marked as preparations M and F, at the manufacturer's recommended quantity of 3 g/dm$^2$. These inhibitors manufactured by a well-known building chemical concern served for comparison of the effectiveness of the tested inhibitors DME and KCR.

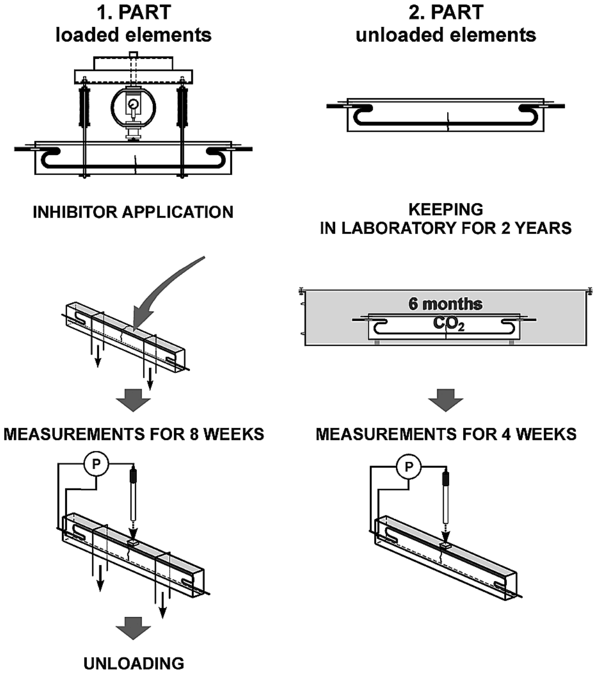

**Fig. 8.** Course of first-stage tests with marginal reinforcement corrosion

After applying inhibitors potentiodynamic measurements were taken, polarizing reinforcement in the range ±100 mV with a speed 2 mV/s. Potentiodynamic measurements were taken every 7 days for 8 weeks. After this period the loading system was dismantled, and saturated with inhibitors. Cracked elements were left for 1.5 years inside at room temperature. Later, elements were put in a carbonation chamber, where they were subjected to a $CO_2$ effect at a concentration of 8–14% for 6 months. Afterwards the potentiodynamic measurements were repeated.

After carbonation the elements were very dry, which made it impossible to carry out correctly further electrochemical measurements. For this reason the elements were moistened by dipping in water the part opposite to the concrete cover to a depth of about 10 mm. Polarization tests were begun after 2 days of moistening, when as a result of capillary absorption the concrete cover could correctly conduct electric current.

The results of every electrochemical measurement were obtained in the form of computer print-outs of the course of the cathode and anode polarization curves and the values of, among other things, the corrosion potential $E_{cor}$ and the corrosion current density $i_{cor}$.

The collective specification of corrosion current density values in elements protected by inhibitors with a low level of development in reinforcement corrosion processes (stage I) is shown on Fig. 9.

Directly after inhibitor application there occurred a reduction of corrosion current density value in the crack, remaining for 8 weeks from the application of inhibitors on the concrete cover. The effectiveness of protection was however differentiated. DME compound and KCR mixture at 6 g/dm$^2$ concentration were characterized by the best effect, limiting reinforcement corrosion speed to about 60% for the whole 8 week period. A slightly lower effectiveness reaching 40% was shown by KCR mixture at 3 g/dm$^2$ concentration. Preparation M, used for comparison, caused a reduction in corrosion speed of about 30%, whereas preparation F was the least effective. Directly after introducing preparation F there occurred a corrosion current density reduction, but at the end of 8 weeks of tests current density had increased almost to the level prior to the application of the inhibitor on the concrete.

About two years after protection of the elements with migrating inhibitors the level of development of reinforcement corrosion processes in the crack was very high. In all cases corrosion current density values exceeding 3 μA/cm$^2$ were observed, i.e., at least 3 times higher than the density gained in the initial stage, directly after moistening with NaCl solution.

Work of KCR inhibitor at 3 g/dm$^2$ concentration is characterized by change of polarization curves shown on Fig. 10.

Curve No. 1 was gained after reinforcement corrosion initiation, directly before inhibitor application. After introduction of the inhibitor curve No. 2 moved toward higher potential values and lower corrosion current densities. After two years and carbonation the-

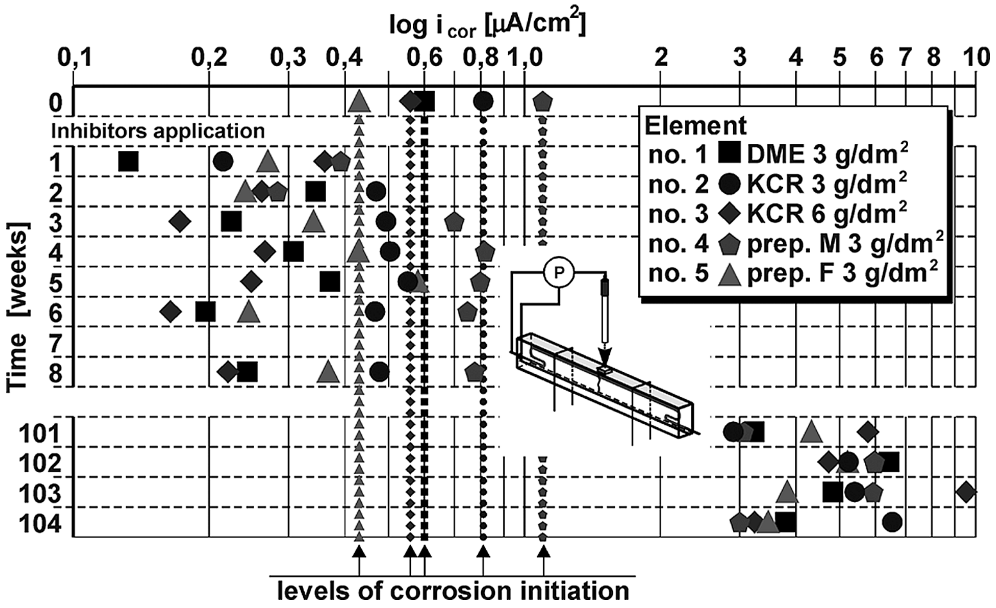

**Fig. 9.** Results of tests on inhibitor effectiveness in elements with a low level of development in reinforcement corrosion processes

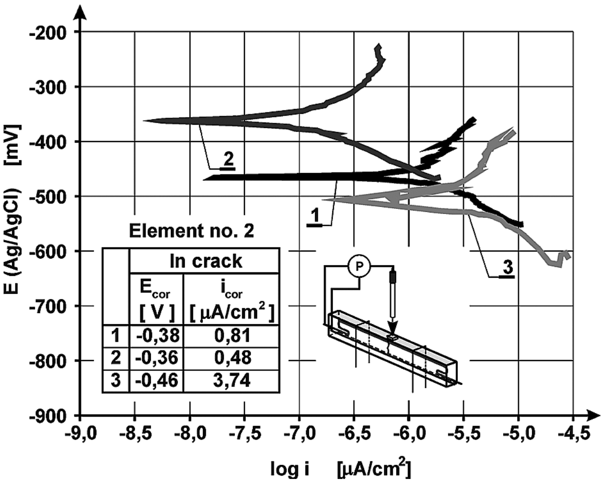

**Fig. 10.** Polarization curves obtained from element number 2: 1 – before inhibitor application, 2 – after KCR inhibitor application with 3 g/dm$^2$ concentration, 3 – two years after inhibitor application and carbonation

re occurred a displacement of curve No. 3 toward lower potential values than occurred on the curve before inhibitor application (No. 1). Polarization curve displacements were accompanied by the changes of corrosion current density values towards curve No. 1 – a reduction after direct work of inhibitor (curve No. 2) and an increase after two years (curve No. 3).

Intensification of reinforcement corrosion speed in the crack two years after applying inhibitors to the concrete surface was most probably caused by physico-chemical properties of the applied inhibitor and its interaction with resulting products in the concrete environment. These substances are characterized by low viscosity and high volatility. For these reasons, especially in the crack, after the elapse of a certain period of time there could occur a reduction in inhibitor concentration. Reactivation of corrosion processes also directly facilitated the presence of an aggressive environment for reinforcement exposed in the crack.

An additional factor intensifying reinforcement corrosion could have been the occurrence of a big-cathode-small-anode effect, in which the iron passing to the solution in the crack is cumulated (Kondratova *et al.* 2003). It should be remarked, that applied inhibitors could be efficient only in the case of chloride corrosion, whereas additional carbonation of concrete could stop their work or even cause an increase in aggressiveness (Ngala *et al.* 2002).

## 5. Stages and results of tests for high level reinforcement corrosion development

Tests on elements in which advanced reinforcement corrosion developed (stage 2) were divided into two parts. The course of test is shown in Fig. 11.

On the surface of two loaded elements Nos. 6 and 7 and two non-loaded elements Nos. 10 and 11 inhibitor KCR was applied at a basic concentration of 3g/dm$^2$. Two remaining loaded elements Nos. 8 and 9 and two non-loaded elements Nos. 12 and 13 were left without inhibitor and treated as a control comparison. Measurements of loaded elements were carried out for 14 weeks, whereas on non-loaded elements, for 9

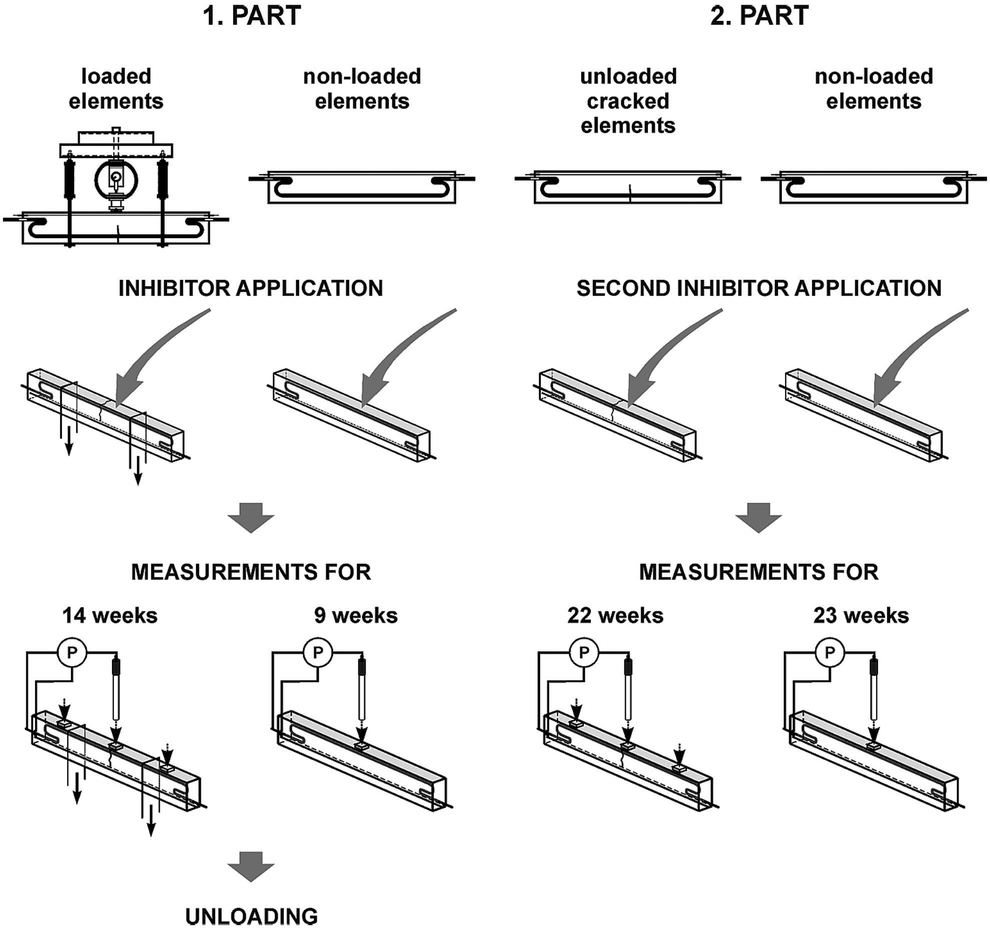

**Fig. 11.** Course of second stage tests with advanced reinforcement corrosion

weeks. Afterwards the loading system was dismantled from the cracked elements, and elements Nos. 6, 7, 10 and 11 were again saturated with KCR inhibitor at a concentration of 3 g/dm$^2$. After renewal of protection treatment potentiodynamic measurements were taken over the ensuing 22 weeks on unloaded cracked elements and for 23 weeks on non-loaded elements. During electrochemical measurements a wider range of reinforcement polarization was used, from –150 mV to +1000 mV, in order to reproduce a complete cathode curve. For the whole test period the elements were kept on a grate, over water, to ensure proper humidity of the concrete.

Results of the corrosion current density measurements in loaded cracked elements saturated with KCR inhibitor are shown in Fig. 12. Fig. 13 shows returned values of corrosion current densities in the loaded and cracked control elements without inhibitor. Corrosion current densities determined in non-loaded elements protected with KCR inhibitor and in the control elements without inhibitor are included in Fig. 14.

In loaded elements with significantly developed reinforcement corrosion the application of KCR inhibitor did not cause a reduction of corrosion current density in the crack. In element No. 6 directly after inhibitor application the corrosion current density value increased, and afterwards reduced slightly, remaining however below the level prior to inhibitor application. After repeated application of inhibitor there was still no reduction in corrosion. The results of measurements showed even an increase in corrosion. Similar results were gained at a 20 cm distance from one side of the crack. On the second side of the crack corrosion current density first increased, then afterwards reduced to below the level initiated in chloride activity. After repeated inhibitor application corrosion current densities showed almost no change.

In the crack of element No. 7 application of KCR inhibitor caused an increase in corrosion. The repeated application of inhibitor caused high and unstable changes in corrosion current densities – alternately reduction and increase in corrosion. Similar results were returned in one place beyond the crack. On the reverse

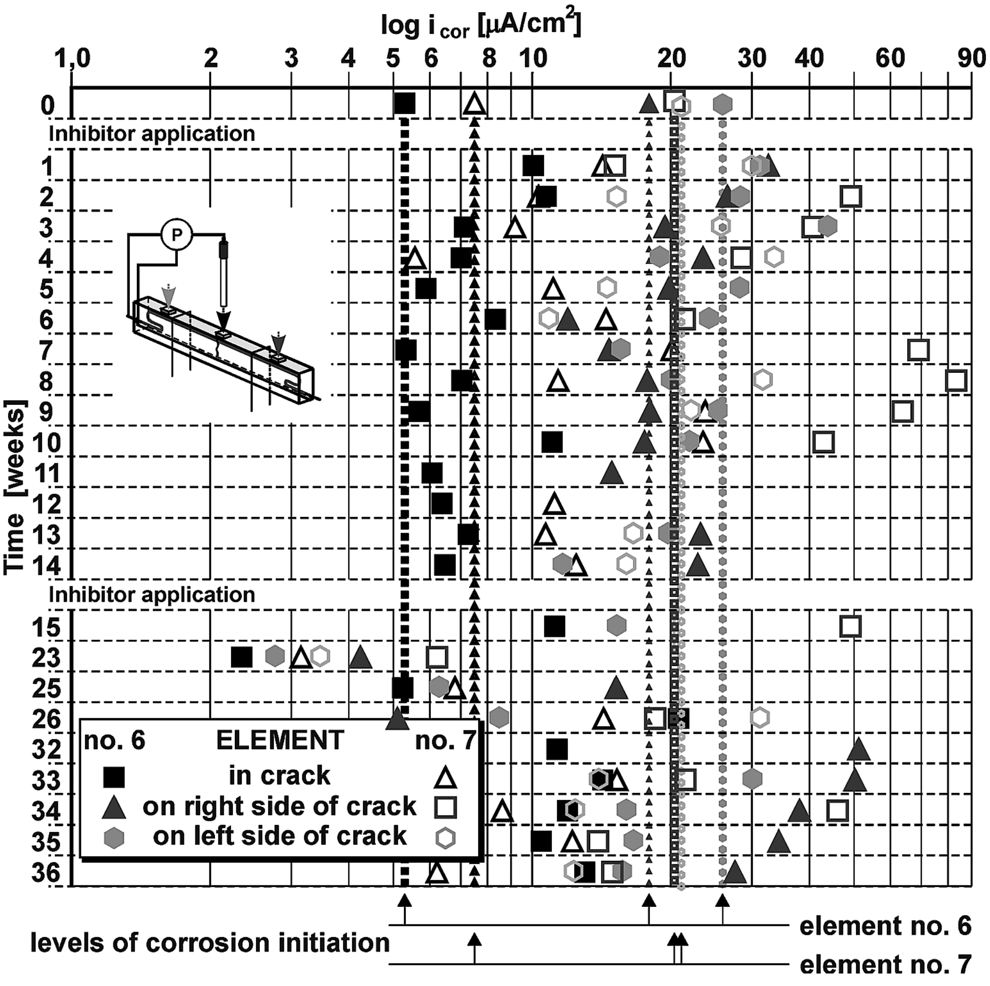

**Fig. 12.** Results of electrochemical tests on reinforcement with advanced corrosion in KCR saturated inhibitor, with loaded and cracked elements: a) number 6, b) number 7

side of the crack the first application of inhibitor caused high and unstable changes in corrosion current densities – reduction and acceleration of corrosion speed. After repeated application of inhibitor corrosion current density was reduced and remained slightly below the level caused by chlorides.

Comparison of results gained in loaded elements Nos. 6 and 7 (Fig. 12) saturated with inhibitor and loaded elements Nos. 8 and 9 without inhibitor (Fig. 13) indicates that with a high level of corrosion development in cracked concrete cover the KCR mixture was ineffective.

After applying the KCR mixture to non-loaded element No.10 an increase in corrosion current density was noticed, and it continued to increase when application of the substance was repeated. In a second non-loaded element No. 11 the action of the KCR inhibitor caused alternately a reduction and an increase in corrosion speed in comparison with the initial level. Similar changes in corrosion current density were found in control elements Nos. 12 and 13 without inhibitor.

The corrosion current density values presented in Fig. 14 show that also in non-loaded elements with average development of reinforcement corrosion KCR inhibitor proved to be ineffective.

The lack of expected protective action of the KCR inhibitor in elements with reinforcement subject to advanced corrosion (loaded and cracked) and average developed corrosion (non-loaded elements) is seen in the shape of polarization curves. In all elements these curves run in a similar way to that shown in Fig. 15 diagram for non-loaded element No. 10. Before initiation of corrosion on curve No. 1 pitting potential was seen. The corrosion arising suited curve 2, while pitting potential was beyond the range of measurement. After inhibitor application curves 3 and 4 were derived, the shapes of which were almost the same as curve 2, though corrosion current densities were higher. After repeated application of KCR inhibitor curves 5 and 6 are derived, only slightly differing from previous curves.

Lack of inhibitor effectiveness in elements with strongly developed corrosion may be caused by very

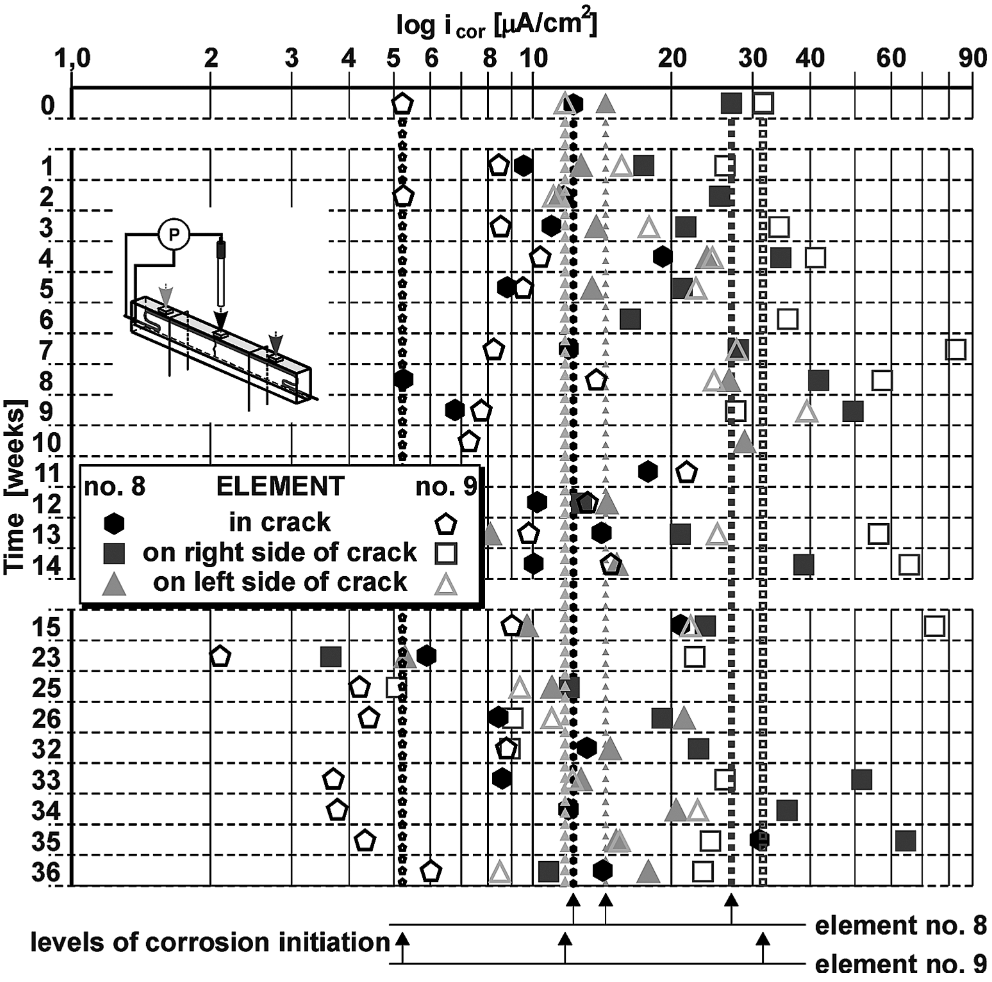

**Fig. 13.** Results of electrochemical tests on reinforcement with advanced corrosion in loaded and cracked comparative elements without inhibitor: a) number 8, b) number 97

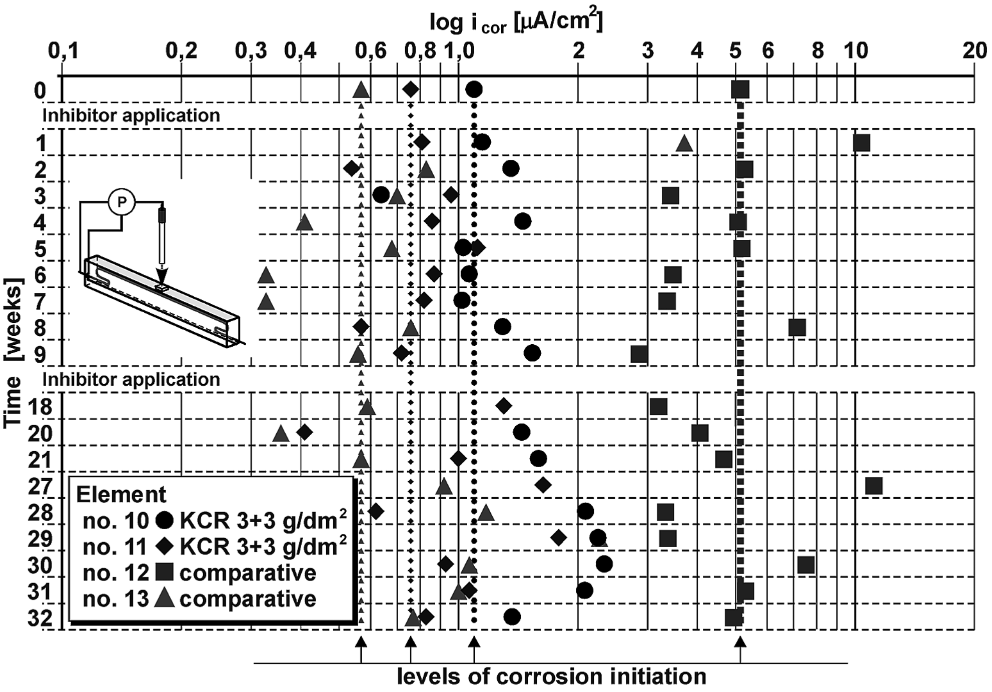

**Fig. 14.** Results of electrochemical tests on reinforcement with average corrosion in unloaded element numbers 10 and 11 saturated with KCR inhibitor and numbers 12 and 13 without inhibitor

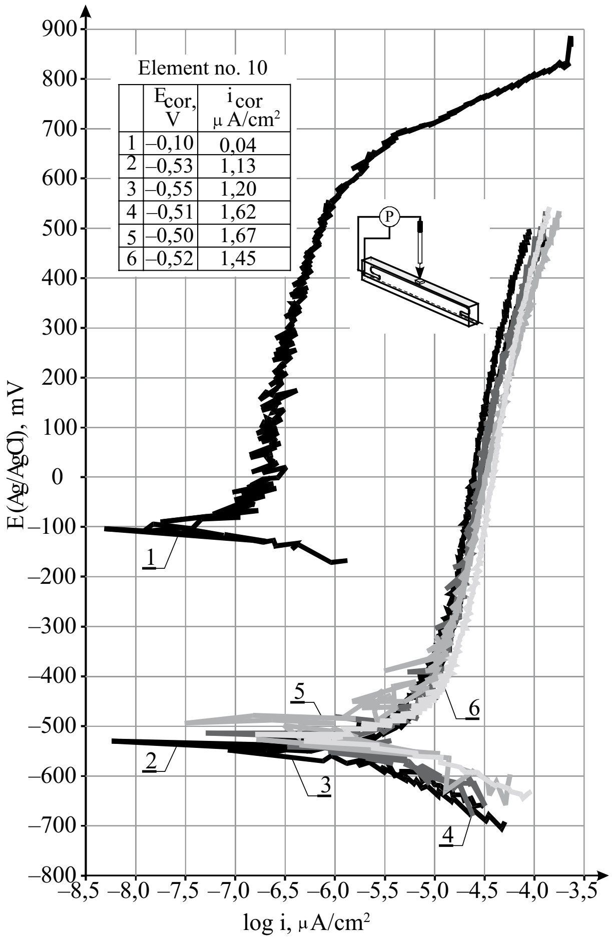

**Fig. 15.** Polarization curves obtained in unloaded element number 10 protected with KCR inhibitor: 1 – in passive state before corrosion initiation, 2 – after initiation of corrosion, 3 – directly after inhibitor application, 4 – after 9 weeks of inhibitor action, 5 – after second inhibitor application, 6 – at the end of the measurements

advanced electrode processes occurring on reinforcing steel surfaces. As indicated in (Alonso *et al.* 1996) the reduction of already existing corrosion processes is more difficult than preventing steel depassivation. Moreover inhibitor concentration at the reinforcing steel surface may not be sufficient due to the high possibility of its component parts being combined with corrosion products. In the case of non-cracked elements concrete cover makes inhibitor penetration difficult, which can cause lower inhibitor concentrations at the level of reinforcement in comparison to cracked elements. Furthermore, corrosion caused by chlorides increases significantly the active steel surface, which means that to stop the development of corrosion it is necessary to considerably increase inhibitor concentration to more than is assumed before the onset of corrosion processes or by an already low level of corrosion in progress.

## 6. Summary

For testing the degree of reinforcement corrosion reduction in conditions similar to those occurring in reinforced concrete the compounds DME and KCR were chosen. In selected tests they have shown the best properties and have not got worse protection properties of pore solution than in natural conditions (lack of carbonation or chlorides presence).

The protective effectiveness of these compounds has been established with respect to the action of stresses, concrete cover cracks and two levels of reinforcement corrosion development – marginal and advanced. Test results of the effectiveness of the selected compounds DME and KCR have been compared with inhibitors called preparation M and F, manufactured by well-known building chemical companies. In cracked elements with marginal reinforcement corrosion ($i_{cor}$ < 1 μA/cm$^2$) directly after the application of the DME and KCR compounds and preparations M and F there occurred a reduction in the corrosion speed, but DME and KCR compounds worked more effectively. 2 years after inhibitor application to the cracked elements with marginal reinforcement corrosion results of tests show the occurrence of a steep increase in corrosion speed – both when DME and KCR have been used and the preparations M and F.

In cracked elements with advanced reinforcement corrosion ($i_{cor}$ ≅ 5 μA/cm$^2$) no success has been achieved in reducing corrosion to date using the most effective inhibitor KCR– irrespective of higher dosage and repeated application. Similarly it has not been possible to reduce reinforcement corrosion with the same inhibitor in non-loaded and non-cracked elements with average reinforcement corrosion ($i_{cor}$ > 0,5 μA/cm$^2$).

Results of the tests indicate the necessity of a very cautious use of migrating inhibitors for reinforced structure protection. In choosing inhibitor protection consideration should be given to the stage of development in the reinforcement corrosion process, the degree of concrete cover cracking, the period of eventual repetition of treatment, the choice of inhibitor dosage to guarantee achievement of expected effectiveness.

## References

Alonso, C.; Andrade, C.; Argiz, C.; Malric, B. 1996. $Na_2PO_3F$ as inhibitor of corroding reinforcement in carbonated concrete, *Cement and Concrete Research* 26(3): 405–415. doi:10.1016/S0008-8846(96)85028-9

Andrade, C.; Alonso, C. 1996. Corrosion rate monitoring in the laboratory and on-site, *Construction and Building Materials* 10(5): 315–328. doi:10.1016/0950-0618(95)00044-5

Andrade, C.; Alonso, C.; Acha, M.; Malric, B. 1992. Preliminary testing of $Na_2PO_3F$ as a curative corrosion inhibitor for steel reinforcements in concrete, *Cement and Concrete Research* 22: 869–881. doi:10.1016/0008-8846(92)90111-8

Falewicz , P.; Klakočar-Ciepacz, M.; Kuczkowska, S.; Zybura, A. 2005. Electrochemical testing of corrosion process in a reinforcement of a cracked concrete, *Archives of Civil Engineering* LI (4): 561–585.

Gaidis, J. M. 2004. Chemistry of corrosion inhibitors, *Cement & Concrete Composites* 26: 181–189. doi:10.1016/S0958-9465(03)00037-4

Holloway, L.; Nairn, K.; Forsyth, M. 2004. Concentration monitoring and performance of a migratory corrosion inhibitor in steel-reinforced concrete, *Cement and Concrete Research* 34.

Jamil, H. E.; Shriri, A.; Boulif, R.; Montemor, M. F.; Ferreira, M. G. S. 2005. Corrosion behavior of reinforcing steel exposed to an amino alcohol based corrosion inhibitor, *Cement & Concrete Composites* 27: 671–678. doi:10.1016/j.cemconcomp.2004.09.019

Klakočar-Ciepacz, M. 2002. Badania porównawcze inhibitujących właściwości związków organicznych w modelowej cieczy porowej [Comparative tests of organic compound inhibiting properties in model pore solution], *Ochrona przed korozją* 4: 95–99.

Klakočar-Ciepacz, M.; Falewicz, P. 2003. Poszukiwanie nowych mieszanek inhibitorów migrujących [Search of new mixtures of migrating inhibitors], *Ochrona przed korozją* 46: 68–71.

Kondratova, I. L.; Montes, P.; Bremner, T. W. 2003. Natural marine exposure results for reinforced concrete slabs with corrosion inhibitors, *Cement & Concrete Composites* 25: 483–490. doi:10.1016/S0958-9465(02)00088-4

Mammoliti, L.; Hansson, C. M.; Hope, B. B. 1999. Corrosion inhibitors in concrete. Part II: Effect on chloride threshold values for corrosion of steel in synthetic pore solutions, *Cement and Concrete Research* 29: 1583–1589. doi:10.1016/S0008-8846(99)00137-4

Montes, P.; Bremner, T. W.; Lister, D. H. 2004. Influence of calcium nitrite inhibitor and crack width on corrosion of steel in high performance concrete subjected to a simulated marine environment, *Cement & Concrete Composites* 26: 243–253. doi:10.1016/S0958-9465(03)00043-X

Morris, W.; Vázquez, M. 2002. A migrating corrosion inhibitor evaluated in concrete containing various contents of admixed chlorides, *Cement and Concrete Research* 32: 259–267. doi:10.1016/S0008-8846(01)00669-X

Ngala, V. T.; Page, C. L.; Page, M. M. 2002. Corrosion inhibitor systems for remedial treatment of reinforced concrete. Part 1: calcium nitrite, *Corrosion Science* 44: 2073–2087. doi:10.1016/S0010-938X(02)00012-4

Phanasgaonkar, A.; Cherry, B.; Forsyth, M. 1997. Organic Corrosion Inhibitors; How Do They Inhibit and Can They Really Migrate Through Concrete? *CAP'97*, Paper 054, Australia, 1997.

Tullmin, M.; Mammoliti, L.; Sohdi, R.; Jansson, C. M.; Hope, B. B. 1995. The passivation of reinforcing steel exposed to synthetic pore solution and the effect of calcium-nitrite inhibitor, *Cement Concrete and Aggregates* 17(2): 134–144.

## ARMATŪROS KOROZIJOS EKSPERIMENTINIAI TYRIMAI NAUDOJANT ORGANINĖS KOROZIJOS LĖTIKLIUS

### A. Śliwka, A. Zybura

**Santrauka**. Straipsnyje pateikti lėtiklių KCR ir DME efektyvumo eksperimentinių tyrimų rezultatai. Eksperimentiniuose tyrimuose apkrautiems betoniniams elementams taikyti tiesinės poliarizacijos metodai. Įvairios lėtiklių aktyvumo trukmės, supleišėjusio betono apsauginio sluoksnio ir skirtingų armatūros korozijos laipsnių išsivystymas eksperimentų dalyse yra įvertintas. Lėtikliai tik iš dalies veiksmingi esant žemam korozijos išsivystimo lygiui pradinėse stadijose, tačiau po dvejų metų jų apsauginis darbas nėra įrodytas. Kai yra didelė armatūros korozija, nėra nustatyta jos laipsnio sumažėjimo, netgi tuoj pat panaudojus lėtiklius.

**Reikšminiai žodžiai:** betonas, lėtiklis, korozija, efektyvumas, apsauga, armatūra, gelžbetonis.

**Adam ZYBURA.** PhD, Prof. and DSc at the Eng. Department of Building Structure, Silesian University of Technology. The author and co-author of 8 monographs, 2 manuals, 94 scientific and technical articles and more than 90 papers on domestic and international conferences. Research interests: structural problems of building engineering, durability and protection against corrosion of concrete structures.

**Andrzej ŚLIWKA**. PhD, MSc, Eng. Department of Building Structure, The Silesian University of Technology. Currently he works as an assistant in the Department of Building Structures at the same University. Research interests: problems of corrosion and reinforced concrete inhibitor protections.