

Nondestructive methods for determination of reinforcement steel corrosion in concrete

Corrosion is the result of the reaction between a material and its environment. Corrosion of the rebar steel may occur under certain conditions in the reinforced concrete structures. The combination of concrete and reinforcement steel was considered optimal, but the practice has revealed the insufficient durability of these structures, the main factor of structural deterioration being the corrosion of reinforcement in concrete. The maintenance and repair of bridges and buildings for their safety requires effective inspection and monitoring techniques for assessing the reinforcement corrosion. Providing of structural safety, that is, regular maintenances and timely repairs require application of efficient techniques of monitoring and control of corrosion of reinforcement in concrete. These methods should enable identification of the degree of damage, and thus indicate the severity of the problem at the moment of inspection. This paper deals with implementation of various non-destructive methods of detection and monitoring of progress of reinforcement corrosion process in concrete, with the emphasis on the method used by CANIN (Corrosion Analyzing Instrument) apparatus. The principle of the method is based on the measuring of the electric potential which is detected on the surface of concrete and which is generated as a result of the electro-chemical corrosion process of the reinforcement.

Key words: reinforcement corrosion, determination, monitoring, nondestructive methods, CANIN

1. INTRODUCTION

It is well known that under certain conditions in the reinforced steel structures or certain structural elements the reinforcement steel, corrosion may commence. The degree of reinforcement corrosion may vary significantly, from the initial phase to the very advanced corrosion, on which basis various remedial structural measures should be undertaken. Corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete construction worldwide, particularly road infrastructure facilities and certain industrial facilities [1]. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface. After initiation of the corrosion process, the corrosion products (iron oxides and hydroxides) are usually deposited in the restricted space in the concrete around the steel. Their formation within this restricted space sets up expansive stresses, which crack and spall the concrete cover. This in turn results in progressive deterioration of the concrete. As a result, the repair costs nowadays constitute a major part

of the current spending on infrastructure. Quality control, maintenance and planning for the restoration of these structures need non-destructive inspections and monitoring techniques that detect the corrosion at an early stage. Corrosion loss consumes considerable portion of the budget of the country by way of either restoration measures or reconstruction. There have been a large number of investigations on the problems of deterioration of concrete and the consequent corrosion of steel in concrete. Properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could effect enormous saving. Moreover, the repair operation themselves are quite complex and require special treatments of the cracked zone, and in most instances the life expectancy of the repair is limited. Accordingly, corrosion monitoring can give more complete information of changing condition of a structure in time [2-5].

Many of the strategic reinforced and prestressed concrete structures have started showing signs of distress with in a short period usually the condition of the structures is monitored by visual inspection and remedial measures are resorted to only when the condition becomes very serious by way to heavy rusting of steel reinforcements followed by cracking and spalling on concrete. It is desirable to, monitor the condition of such strategic structures right from the construction stage by carrying out periodic corrosion surveys and maintaining a record of data.

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For measurement of the corrosion rate of reinforcing steel in concrete, many electrochemical and non-destructive techniques are available for monitoring corrosion of steel in concrete structures.

In this paper, in detail was presented the non-destructive method of determination of corrosion process of the reinforcement steel applying the CANIN device (**C**orrosion **A**nalysing **I**nstrument). The method principle is based on the measurement of the electric potential detected on the surface of concrete generated as the result of the electrochemical process of reinforcement corrosion. The method is applicable both in a laboratory and in the field as well on all the reinforcement-concrete structural elements. The device accuracy is such so as to facilitate detection of conditions for concrete reinforcement corrosion also in the cases when the corrosion of the reinforcement itself has not yet commenced or is in the initial phase.

2. CORROSION MONITORING TECHNIQUES

2.1. Half cell potential measurement

Monitoring of open circuit potential (OCP) is the most typical procedure to the routine inspection of reinforced concrete structures [6-8]. Its use and interpretation are described in the ASTM C 876 Standard Test Method for Half-Cell Potential of Reinforcing Steel in Concrete [9].

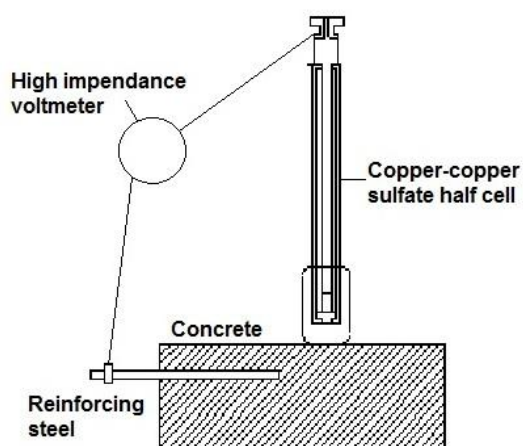


Figure 1 - Galvanization element formed by reinforcement rod and copper sulphate electrode with voltmeter (schematic)[9]

The device for examination of corrosion degree of the steel in concrete (figure 1) must possess a so-called semi-cell, most often copper – copper sulphate, in the form of a copper-sulphate solution in a vessel made of a material which does not react with this substance. The method utilizes the fact that in the semi-cell reaction:



Occurs a potential of saturated copper-copper sulphate semi-cell which can be expressed in Volts. The potential can be expressed using other, not only copper-copper sulphate semi-cells, but the measured values are converted to an equivalent potential corresponding to usage of copper-copper sulphate semi-cell.

Due to corrosion, occurs a semi-cell reaction which as a consequence has an equilibrium potential between electrolyte and metal. In order to measure the value of the potential, it is necessary to close the currency circuit. This can be accomplished by creating a connection via a conductor (wire) between the reinforcement rod and the semi-cell. A voltmeter is installed, measuring the electric potential between the reinforcement steel and the semi-cell.

Also, between the concrete and the semi-cell a low-resistant liquid should be present, in order to serve as a bridge between concrete and the semi-cell. For this purpose, a sponge is used, which is soaked in solution of electrical low-resistance. The sponge should envelop the top of the semi-cell and provide continuity between the top of the semi-cell and the concrete element via a strong pressure on the concrete surface. The duration of the pressure of the semi-cell electrode sponge section must be sufficient to allow the graphic presentation of the measured potential on the display, which is a constituent part of the measuring device, which will be signaled by a warning sound or in some other manner.

The spacing between the measuring points is not precisely defined, and it is specifically determined for concrete cases. Yet, measuring with too small a spacing of measuring points does not have a point, as almost same values will be obtained for adjacent measuring points. On the other hand, if the measuring points are too wide apart, corrosion in a part of the structural element which is being examined may be overlooked. At any rate, the spacing must remain constant on the examined element. Measuring is defined as a numbered folder in the device.

The surface on which the measuring is taken is divided into fields with dimensions defined according to the conditions and type of measuring. The same spacing and distribution of fields is defined through the given options on the apparatus, as a grid of certain dimensions, in X and Z directions. The potential in one field is measured (or if several electrodes are used, it can be measured in several fields simultaneously). The gauge pointer on the display indicates in which direction the following measurement will be taken. If the direction or orientation is changed, it should be defined prior to the following measurement.

In case of bridges, spacing between the measuring points can be larger than 1m, but the spacing could be reduced in the places where the difference of the potentials in the adjacent fields exceeds 150mV, that is in the areas of high corrosion activity. The minimum spacing should allow a difference of at not less than 100mV between the adjacent readings. In that case a new folder is formed, as if it is a different element.

Electric connection with the reinforcement can be realized by an earthed connector, by soldering or welding. To reduce the impedance, one should grind or sand – paper the rod at the point where it is connected. Often, the layer of concrete should be locally removed to access the reinforcement. The reinforcement is connected to the positive terminal on the volt-meter, and the semi-cell to the negative one. If the measurements are repeated after some time interval, they should be performed on the same measuring points as the previous ones.

The potential of the semi-cell is recorded with the accuracy of 0,01 V and if the operation temperature was outside the range 22 ± 5 °C range it is corrected by certain coefficients.

The measuring can be represented by using the equipotential lines (figure 2) or by the cumulative frequency method. In the former case, the areas on the element where corrosion activity is possible are graphically divided, and in the latter the sizes of the areas affected by corrosion on the concrete element are indicated.

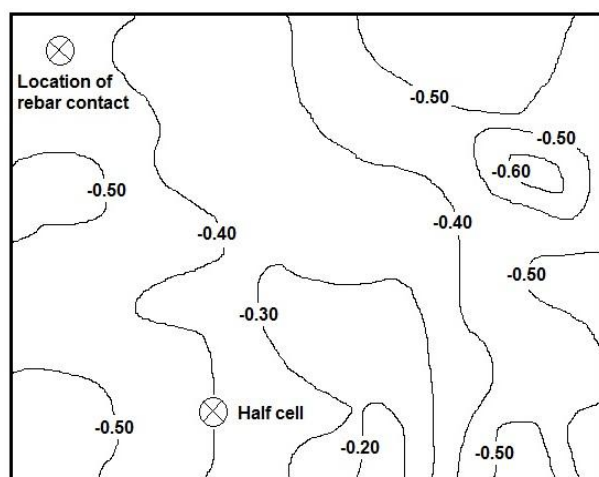


Figure 2 - Results of measurements using the equipotential lines [9]

If the potentials are in the measured area:

- More positive than -0,20 V, there is a probability of 90% that there is no steel corrosion at the moment when the measurement was taken,

- In the range -0,2 V to -0,35 V, the presence of corrosion activity of steel cannot be excluded,
- More negative -0.35 V, there is more than 90% of probability that there is a corrosion activity in the given area at the moment when the measurement was taken.

2.2. Linear Polarization Resistance Measurement (LPR)

The linear polarization resistance technique (figure 3) is a well-established method for determining corrosion rate by using electrolytic test cells (ASTM G 59) [10]. The technique basically involves measuring the change in the open-circuit potential of the electrolytic cell when an external current is applied to the cell. For a small perturbation about the open-circuit potential, there is a linear relationship between the change in applied current per unit area of electrode (Δi) and the change in the measured voltage (ΔE). The ratio $\Delta E/\Delta i$ is called the polarization resistance (R_p). The corrosion rate, expressed as the corrosion current density, is inversely related to the polarization resistance. Note that, for both methods, one terminal must be electrically connected to the reinforcement, that is, physical access to the reinforcement must be provided [6-8].

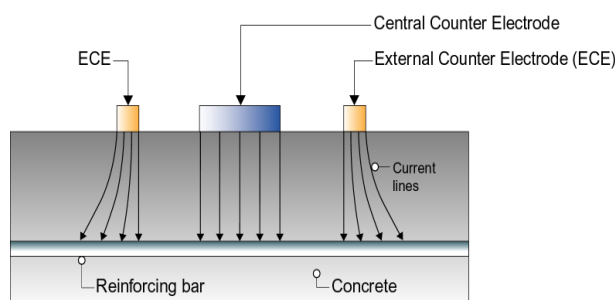


Figure 3 - Linear polarization resistance [8, 11]

When a very small electrical potential (of the order of 10 mV) is applied to the corroding steel, the relationship between potential and current is linear. The polarization resistance, R_p , is the ratio of the applied potential to resulting current and is inversely proportional to the corrosion rate [12]. In order to calculate a corrosion rate with the LPR technique, the following fundamental assumptions must be made [13]:

- uniform corrosion damage;
- the rate controlling step in corrosion is activation polarization (i.e. the ease of stripping electrons from the iron);
- there is a single anodic and a single cathodic reaction;
- the proportionality constant between corrosion rate and R_p must be known;

- the electrical resistance of the solution (i.e. the concrete) is negligible;
- the half-cell potential is stable.

Measurements are performed by applying a potential in the range of ± 10 to 20 mV about the E_{corr} , either as a constant pulse (potentiostatic), or a potential sweep (potentiodynamic), and measuring the current response. Alternatively, a current pulse (galvanostatic) or a current sweep (galvanodynamic) can be applied, and potential response is measured. The RP and, in turn, the corrosion rate is calculated by the instrument.

In fact, of these assumptions, only the third one is applicable to the case of chloride induced corrosion of embedded reinforcement. Despite this, the LPR technique has become increasingly popular for measuring corrosion in the field because: (i) it is a nondestructive technique; (ii) it is simple to apply and (iii) it usually needs only a few minutes for corrosion rate determination [14].

2.3. Cyclic potentiodynamic polarization

Cyclic polarization is relatively non-destructive technique that provides the corrosion rate, corrosion potential and susceptibility to pitting corrosion of the metal in the test environment, as well as giving information about the expected behavior of the steel should its potential be changed by, for example, exposure to stray currents, coupling with other metals or the surrounding concrete becoming anaerobic [6]. Like most electrochemical techniques, cyclic polarization is carried out with three electrodes: a working electrode (the reinforcing steel), a counter electrode and a reference electrode. The potential of the specimen is changed continuously or in steps, while the resulting current is monitored. From a plot of the applied potential versus the logarithm of the resulting current density, the condition of the steel in the present environmental, as well as its potential behavior under other conditions, can be assessed. Cyclic polarization is most useful in the laboratory, for example, to evaluate the behavior of steel in new concrete mixes or the behavior of alternative reinforcing materials in normal concrete. While such tests have been successfully performed in the field by the authors, they suffer the same limitation of LPR that of knowing the polarized area of the steel, as well as taking a longer time to perform.

2.4. Electrochemical Impedance Spectroscopy (EIS)

The electrochemical impedance spectroscopy method, or AC impedance, can determine a number of fundamental parameters related to corrosion kinetics, and it has been extensively used in corrosion research [6-8]. The method analyses the response of

corroding electrodes to small-amplitude alternating signals (AC) that vary in a wide range of frequencies. The input is usually a sinusoidal wave of AC current with magnitude I and frequency f , and the output is a voltage response with magnitude $V(f)$ and phase difference $\phi(f)$ with respect to the current. Figure 4 illustrates the experimental setup [15]. Following this procedure, one determines experimentally the impedance $Z (=V/I)$ as a function of ω , and then tries out different ways of representing the electrode process in terms of its electrical analogue of resistance, capacitance and/or inductance in various arrangements corresponding to the possibilities of the physical model. The three most important physical quantities responsible for the impedance measured in a cell are: (1) The solution (or electrolyte) resistance, (2) The resistance of the interface, and (3) The capacitance of the Double Layer [15-17].

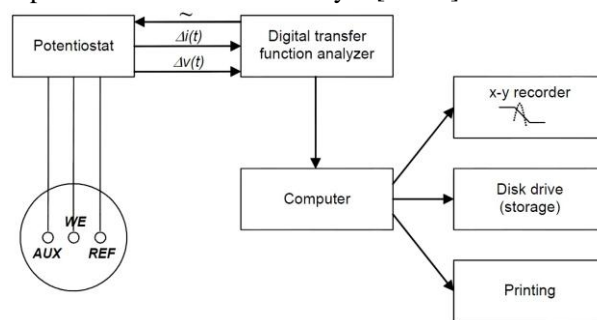


Figure 4 - Instrumentation for conducting EIS [8,15]

2.5. Galvanostatic Pulse Technique

The galvanostatic pulse method is a transient polarization technique working in the time domain. The method set-up is shown in Figure 5.

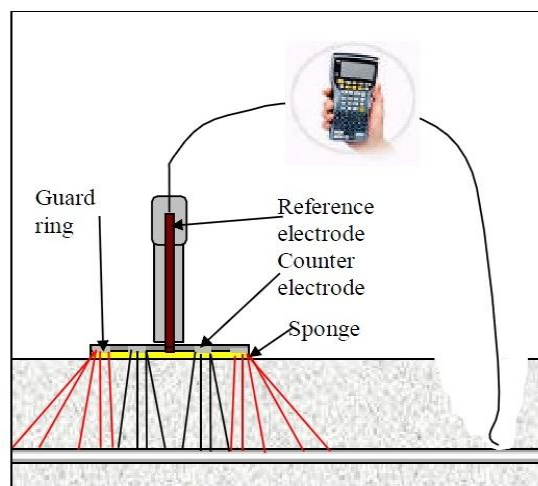


Figure 5: -Set-up of the galvanostatic pulse technique [18]

A short time anodic current pulse is imposed galvanostatically on the reinforcement from a counter electrode placed on the concrete surface. The applied

current is usually in the range of 10 to 200 μA and the typical pulse duration is up to 10 seconds. The reinforcement is polarized in anodic direction compared to its free corrosion potential. The resulting change of the electrochemical potential of the reinforcement is recorded by a reference electrode (usually in the centre of the counter electrode) as a function of polarization time [7, 18, 19]. Typical potential transient response is shown in Figure 6.

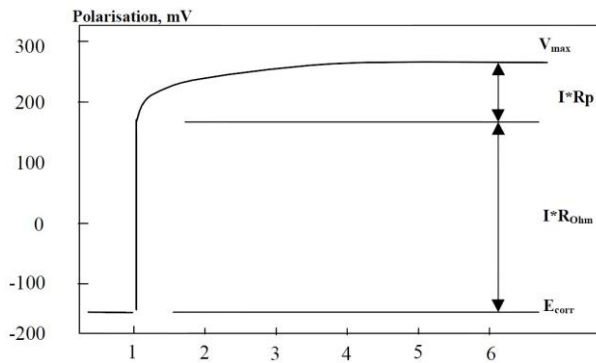


Figure 6 - Typical potential time curve as response to a galvanostatic pulse [18]

When a constant current I_{app} is applied to the system, an intermediate ohmic potential jump and a slight polarization of the rebars occur. Under the assumption that a simple Randles circuit describes the transient behaviour of the rebars, the potential of the reinforcement, $V_t(t)$, at a given time t can be expressed as [20].

$$V_t(t) = I_{app} [R_p[1 - \exp(-t / R_p C_{dl})]] + R_{\Omega},$$

where:

R_p = polarization resistance

C_{dl} = double layer capacitance

R_{Ω} = ohmic resistance

In order to obtain the values of R_p and C_{dl} and the ohmic resistance R_{Ω} has to be evaluated further based on the experimental values. Two different methods, a linearization [21] and an exponential curve fitting procedure [22] have been proposed. For the linearization eqn.(8) can be transformed in a linear form

$$\ln(V_{max} - V_t(t)) = \ln(I_{app} R_p) - t / (R_p C_{dl})$$

where V_{max} is the final (and experimentally unknown) steady potential value reached after long polarization. Extrapolation of this straight line to $t = 0$, using least square linear regression analysis, yields an intercept corresponding to $\ln(I_{app} R_p)$ with a slope of $1/(R_p C_{dl})$. The remaining over potential corresponds to $I_{app} R_{\Omega}$ which is the ohmic voltage drop.

One difficulty with the galvanostatic pulse transient technique is that the response to the pulse has to

have stabilized to give an accurate value for V_{max} . Curtailing the measurements before an equilibrium value for V_{max} has been attained may also lead to errors in the evaluation of R_p and C_{dl} . This technique and those of AC impedance and harmonic analysis suffer from the same difficulty in measuring reinforced concrete structures in the field as does LPR measurement, i.e. the area of steel surface being measured is difficult to quantify.

2.6. Acoustic Emission Analysis

A typical corrosion loss during the corrosion process is illustrated as shown in Figure 7. At phase 1, the onset of corrosion is initiated. As the rate of the corrosion process is controlled by the rate of transport of oxygen and water from the surface of rebar and the corrosion products build up on the corroding surface, the flow of oxygen is eventually inhibited, and thus the rate of the corrosion loss decreases at phase 2. The corrosion process proceeds further corrosion loss at phases 3 and 4 because of anaerobic corrosion. The corrosion penetrates inside the steel and the growth of corrosion products occurs. The phenomenological model of steel presents a two-step process of the onset of corrosion and the growth of corrosion products [23, 24].

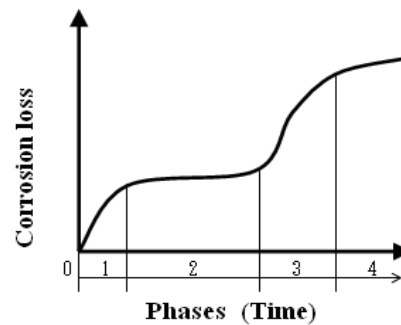


Figure 7 - Typical corrosion loss for steel in seawater immersion [25]

By applying AE techniques, recently it has been reported that concrete cracking arising out of rebar corrosion is effectively detected [26], [27]. AE detection because of the corrosion of rebar is illustrated in Figure 8 [28]. Recently, it is demonstrated that high AE activities are observed twice during the corrosion process [23, 24]. In the case of reinforced concrete, AE activity at phase 1 reasonably corresponds to the onset of corrosion in reinforcement. During phases 3 and 4, not only the growth of corrosion products, but also corrosion-induced cracks in concrete could be generated because of the expansion of corrosion products in reinforced concrete. In the figure, these periods are compared with the chloride concentration at rebar, where two threshold values of 1.2 and 0.3 kg per m^3

concrete are denoted. The latter is equivalent to the lower-bound value for nucleation of corrosion in the Japanese standard [29] and is very low compared with the threshold values assigned for corrosion initiation in many reports. But, right after the chloride concentration becomes higher than the lower-bound, 1st high AE activity is observed which corresponds to phase 1 and the onset of corrosion. At the stage over the upper-bound value of chloride concentration, 2nd high AE activity is observed as phases 3 and 4. It is easily realised that AE hits arising out of concrete cracking is detected at the stage, because the expansion of corrosion products could occur.

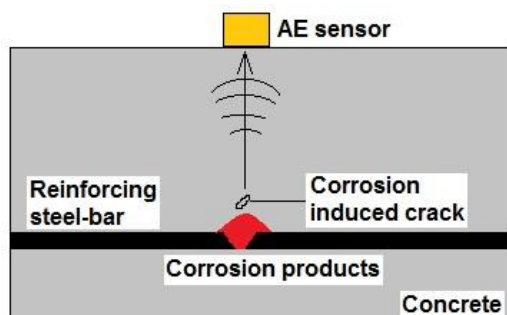


Figure 8 - AE generation because of the corrosion of rebar [28]

Acoustic emission activity was analysed by AE hits and AE event. Here, AE hit is the term to indicate that a given AE channel has detected and processed one AE transient signal. Counting methods of AE signals are ringdown-counting by setting the threshold. By employing a multichannel system, AE wave can be detected in the form of hits on one or more channels. One event is a group of AE hits received from a single source by two or more channels, of which spatial coordinates could be located.

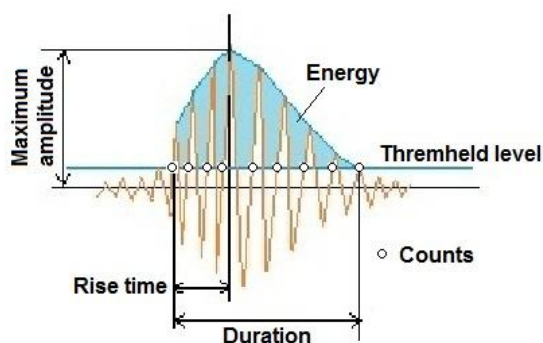


Figure 9 - AE waveform parameters [24]

Characteristics of AE signals were estimated by using two indices of RA value and average frequency [30]. These are defined from such waveform parameters as rise time, maximum amplitude, counts and duration shown in Figure 9. AE sources of active cracks are classified, based on the relationship between these indices.

3. THE PILOT TESTING IN THE LABORATORY USING AN INSTRUMENT CANIN (HALF CELL POTENTIAL MEASUREMENT)

For the tests in laboratory, two concrete cubes from the same batch were made of the C 25/30 class concrete, with the sides of 20 cm. The cubes have steel rods (reinforcement) installed in them, at a distance of 5 cm (figures 10 and 11).



Figure 10 - Appearance of a concrete specimen with installed reinforcement



Figure 11 - Appearance of the device

In order to interpret the results in respect to the actual physical condition of the samples, the corrosion activity was measured immediately after the setting of concrete and 3 weeks later. In order to make a distinction and register the difference in the corrosion activity between the samples, one was cured in fresh water, while the other was cured in salt water, so that the chlorine ions could accelerate the corrosion process. The performed measurements

demonstrated that there is no significant difference in the measured values of electric potential on these two samples. On the sample cured in the salt water, around 2 times more negative value of potential was

measured, which confirms the previous statements. Demo recording of corrosion of reinforcement in concrete is shown in Figure 12 [31].

Object 1

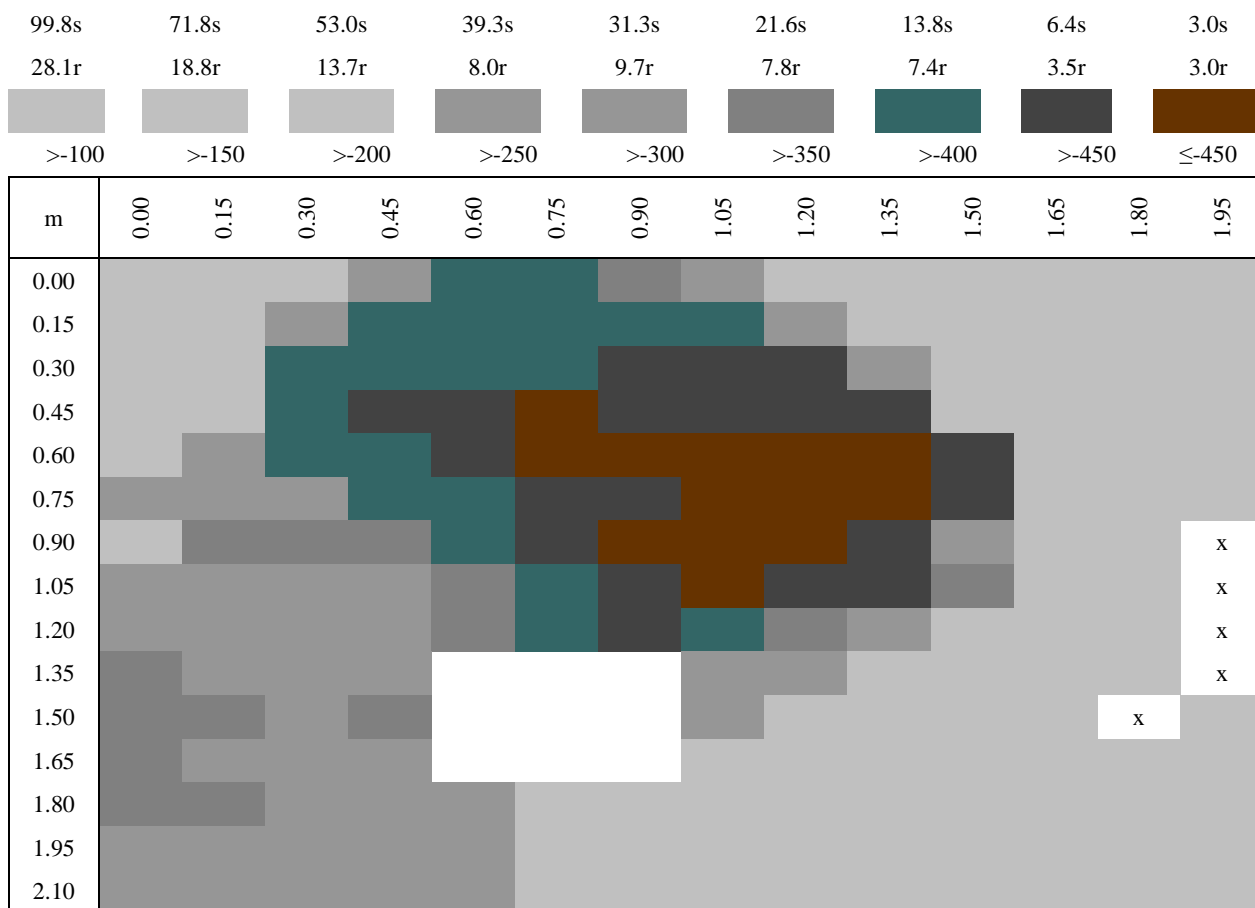


Figure 12 - Showing demo of corrosion of reinforcement in concrete [31]

4. CONCLUSION

Corrosion of the reinforcement in reinforced-concrete structures, especially in the transport infrastructure and certain industrial buildings, after years of service and inadequate maintenance occurs frequently. There are various methods enabling detection of concrete reinforcement corrosion, and accordingly, a variety of recommendations based on the long-lasting studies. One of them is usage of the special CANIN type device, which has been presented in this paper. The first step in the implementation of this method was made, as well as in the interpretation or results, indicating the high probability of detection of corrosive activity in concrete.

A number of electrochemical rebar corrosion measurement techniques available presently are reviewed.

Each technique is reviewed to possess with certain advantages and limitations. To obtain maximum information about the corrosion state of rebar in a particular structure, a combination of measuring techniques is recommended. Although the electrochemical corrosion measurements are usually qualitative and also semi quantitative, significant benefits can be derived from them.

The development of integrated monitoring systems for new and existing reinforced concrete structures could reduce costs by allowing a more rational approach to the assessment of concrete structures. The ability to continuously monitor the cover concrete and steel *in real time* could thus able to provide more information of the current and future performance of the structure. Corrosion monitoring can be a

vital part of planned maintenance and life prediction by giving quantitative information about the development of corrosion as aggressive conditions develop in the concrete due to chloride ingress or carbonation. It can also be used to assess the effectiveness of rehabilitation systems such as coatings or corrosion inhibitors. Installations have been carried out on new structures with long life requirements for planned maintenance and to prevent premature repair requirements.

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IZVOD

NEDESTRUKTIVNE METODE ZA UTVRĐIVANJE KOROZIJE ARMATURE U BETONIMA

Korozija je rezultat reakcije između materijala i njegove okoline. Korozija armaturnih čelika može se pojaviti pod određenim uslovima u armirano betonskim konstrukcijama. Kombinacija betona i armature smatra se optimalnom, ali praksa je pokazala na nedovoljnu trajnost tih struktura. Često je glavni činioc nedovoljne trajnosti armirano betonskih struktura korozija armature u betonu. Obezbeđivanje sigurnosti konstrukcije, to jest, redovno održavanje i blagovremene popravke zahtevaju primenu efikasnih tehnika za praćenje i kontrolu korozije armature u betonu. Ove metode treba da omoguće identifikaciju stepena oštećenja i na taj način ukažu na ozbiljnost problema u trenutku inspekcije. Ovaj rad daje prikaz različitih nedestruktivnih metoda detekcije i praćenja napretka procesa korozije armature u betonu, s naglaskom na metode koje koriste Canin aparata. Princip metode se zasniva na merenju električnog potencijala koji se detektuje na površini betona, a koji je nastao kao rezultat elektro-hemijskog procesa korozije armature.

Ključne reči: korozija armature, monitoring, metode bez razaranja, CANIN

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