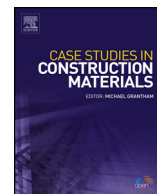


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Case study

Critical analysis of laboratory measurements and monitoring system of water-pipe network corrosion-case study.



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ABSTRACT

Case study of corrosion failure of urban water supply system caused by environmental factors was presented. Nowadays corrosion monitoring of water distribution systems is an object of major concern. There is possibility of application broad range of techniques like gravimetric and electrochemical. Both kinds of techniques can be applied in laboratory and field conditions. In many cases researches limit the case analysis to measurements in laboratory conditions. Presented work contain critical analysis of results obtained in laboratory and field conditions based on corrosion monitoring of three pipelines systems failure in Krakow.

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1. Introduction

Carbon steel is still one of the most common and popular construction material, despite the high development of materials. Carbon steel, the most widely used as engineering material, is counted for approximately 94% of the annual production in United States. Relatively limited corrosion resistance of carbon steel do not change the fact that it is used in large tonnages in marine applications, pipelines, mining, chemical processing, nuclear power and fossil fuel power plants, transportation, petroleum production and refining, construction and metal-processing equipment (Koch et al., 2005; Morgadoa and Sousa e Brito, 2015; Al-Saleh, 2015; Atkins et al., 2015).

The economic cost due to corrosion can hardly be overestimated. As calculated by the National Association of Corrosion Engineers, in the USA alone, the total cost involved in 2012 amount to above \$1 trillion, no less than 6.2% of GDP (Hoog et al., 2014; Slepski et al., 2014).

Corrosion of water distribution systems is a widespread issue that can cause unwanted changes in water quality and failures of the water distribution systems. These considerations suggest that a complete monitoring program and water treatments controlling and guaranteeing the water quality are necessary (Bigoni et al., 2014).

Krakow is large city in Southern Poland. The beginning of the water-pipe network of Krakow is dated to 15 February 1901. With regard to over 100-year exploitation of water-pipe network, it is characterized by essential age differentiation. In the city pipelines from the first decades of the distribution system operating period still exists, of the age over 50 years. Krakow is

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divided into separate water-pipe zones of supplying fed from independent sources which are 4 top water intakes supplied from: the Raba River, the Rudawa River, the Dlubnia River and the Sanka River and one underground intake placed in Mistrzejowice. Presented case study comply with corrosion of three water distribution systems from sources named as Bielany, Rudawa and Dlubnia and its water average production is counted for 17.9; 37.7 and 28.5 m³/d respectively (Zimoch, 2005). Total length of steel pipeline is equal to over 600 km. In recent years number of corrosion related problems with pipeline significantly increased and was source of some leakage, outages in water supply and discoloration events. The presence of large number of failures forces creation of corrosion rate monitoring system.

Monitoring program can be realized by controlled laboratory studies or field survey or combination of both. Laboratory studies are mostly in the form of electrochemical impedance spectroscopy and Tafel polarization. Overall corrosion rates can be estimated by means of fitting, typically using the Butler–Volmer equation or its variants (Flitt and Schweinsberg, 2005; Mansfeld, 2005; McCafferty, 2005; Zhang et al., 2009). The complexity of predicting responses of corrosion processes and metal release to long- and short-term variations of drinking water properties and flow conditions, it is mostly critical to monitor these responses in real time (Ishii and Boyer, 2011; Sancy et al., 2010; Volk et al., 2000).

The purpose of this study was to examine the effects of water corrosivity of various rivers using a combination of controlled laboratory studies and a field survey.

2. Experimental

The electrochemical experiments were performed at room temperature, using Ag/AgCl and Pt-mesh as reference and auxiliary electrodes, respectively. The exposed surface of the working electrode in the solution was circular in shape with an area of 1 cm². The working electrode was a cylindrical disc cut from a specimen of S236JR having the chemical composition determined in polish norm no. PN 10020. The working electrode was first prepared using 400–2500 grade abrasive paper, and following this procedure, it was rinsed with distilled water and degreased with acetone.

The EIS measurements were performed using a Reference 600, Gamry Potentiostat/Galvanostat/ZRA supplied by M/S Gamry Instruments (USA). Before EIS measurement, each sample was immersed in the corrosion cell and allowed to stabilize for 2 h. The EIS studies were performed by imposing a sinusoidal voltage of 10 mV amplitude as the open circuit potential of the working electrode. The frequency was varied between 100 kHz and 18 mHz.

The corrosion monitoring system consists of industrial computers performing measurements together with a data transfer system, data control and conditioning systems, a multiplexer-enabling sensor control and sensors placed inside the water pipeline (Orlikowski et al., 2015).

The monitoring system was managed digitally. The digital system includes a data conditioning module and a sequential control module for measurements from individual sensors. The data conditioning system is also directly connected with a measuring computer.

Corrosion processes are monitored automatically, the corrosion rate was measured on the basis of linear polarisation resistance (LPR) measurements. This measurement technique allows for determining the corrosion rate directly during tests (Stern and Geary, 1957).

3. Results and discussion

Impedance, Tafel polarization and monitoring system results of carbon steel exposed to three different waters from Bielany, Dlubnia and Rudawa river are presented. Monitoring system includes the results from 90 days of exposition. Impedance and Tafel polarization measurements were performed in laboratory conditions on water samples collected in 5th day of monitoring system. Obtained impedance spectra are presented on Fig. 1.

The acquired impedance spectra demonstrate a flattened circular shape. In order to obtain more qualitative information of inhibition mechanism the impedance data were analyzed with the use of the electrical equivalent circuit.

The equivalent circuit (Fig. 2) consists the resistor, representing the solution between working and the reference electrodes R_s , in series to a parallel combination of the resistor, R_{ct} , playing the role of the charge transfer (corrosion) resistance and constant phase element CPE. Its impedance, Q is used instead of capacitor due to presence of depressed semicircles in the spectra, and O as a finite-length Warburg diffusion impedance (Cao et al., 2015).

The value of charge transfer resistance is of high importance and decides about the dynamic of the corrosion process. Values of R_{ct} obtained from impedance spectra are presented in Table 1. Values of b_a and b_c Tafel coefficient were obtained by analysis of Tafel slopes in manner taking to account diffusion control. Corrosion rate were calculated using Stern–Geary equation. Tafel polarization curves are presented in Fig. 3.

Table 1 presents values of corrosion current obtained from extrapolation of Tafel curves and by application of Stern–Geary equation. The difference between both obtained results is a consequence of electrolyte resistance contribution which is not differentiated by Tafel polarization. Larger value of electrolyte resistance contribute to more significant error. As a results corrosion current obtained from Stern–Geary equation is more accurate and was used for further corrosion rate calculations.

Corrosion rates (Fig. 4) of steel obtained from monitoring systems in the first 5 days shown similar values for all three rivers, moreover Bielany river in some period of time is described by the highest corrosion rate. After 10 days metal exposed in Bielany river is representing decreasing tendency in the same becoming the smallest value of corrosion rate. Samples

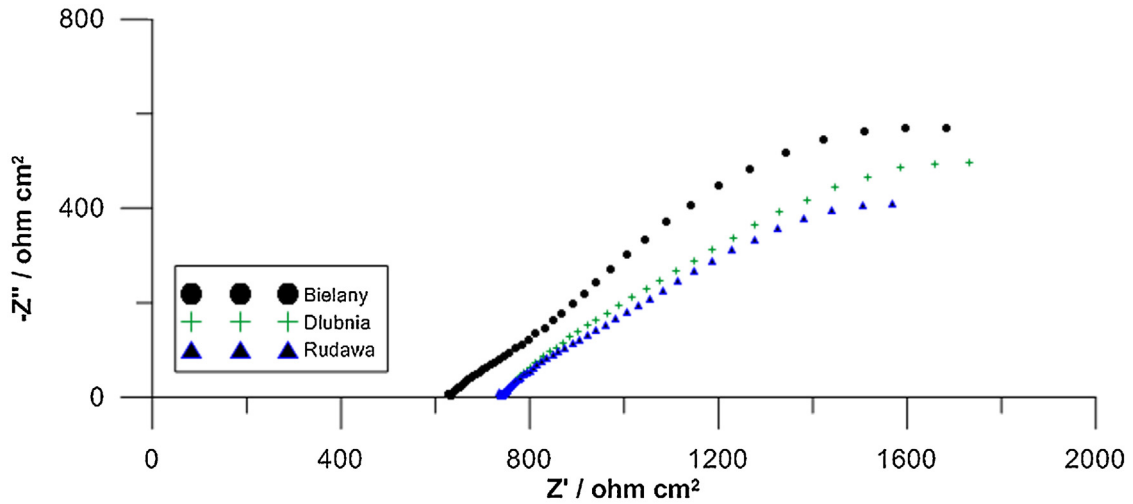


Fig. 1. The Nyquist plots for carbon steel in Bielany, Dlubnia and Rudawa rivers.

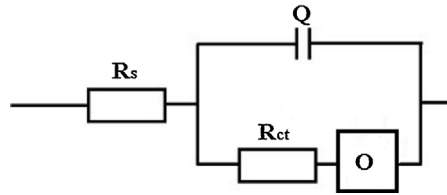


Fig. 2. Equivalent circuit for carbon steel samples in water environment (R_s solution resistance, R_{ct} charge transfer resistance, Q constant phase element, O finite-length Warburg diffusion impedance).

exposed to Dlubnia and Rudawa rivers after 30 days of measurement keeps similar corrosion speeds until the end of presented results of monitoring system.

The Langelier indices are useful in determining the corrosive or scale-forming tendencies of water. Based on the analysis of water composition, the analysis of Langelier indices was conducted. The obtained results of Langelier for Dlubnia, Rudawa and Bielany are as follows: 0.78, 0.10, 0.35.

The Langelier indices of the collected water samples were above zero, which indicates low corrosion aggressiveness of all river waters.

Comparison of laboratory and field survey results clearly show significant differences. Especially results of monitoring system describes changing environmental conditions. It has to be mentioned that river are open systems and chemical composition, temperature and other important features of water can change during the time. Below are described main conditions which can influence values of corrosion rate by laboratory measurement and in field.

3.1. Environmental factors

The tap water is generally known to be corrosive in the pH range at 6.5–7.5. And the degree of corrosion varies depending on the types of raw water. Water is collected from the river; therefore, as a result, considerable differences occur in the chemical and physical composition of water in the annual cycle. In the summer time, water temperatures rise, thus increasing corrosion aggressiveness of water.

Table 1
Results obtained in laboratory conditions.

	b_A [V/dec]	b_C [mV/dec]	R_{ct} [Ω] from impedance	R_s [Ω] from impedance	i_{corr} [A] Stern–Geary equation	i_{corr} [A] Tafel Polarization	CR [mm/ year]
Dlubnia	0.254	0.272	1231	741	4.633E-05	2.892E-05	0.5046
Rudawa	0.336	0.308	1141	734	6.115E-05	3.721E-05	0.6661
Bielany	0.264	0.362	1578	625	4.200E-05	3.009E-05	0.4576

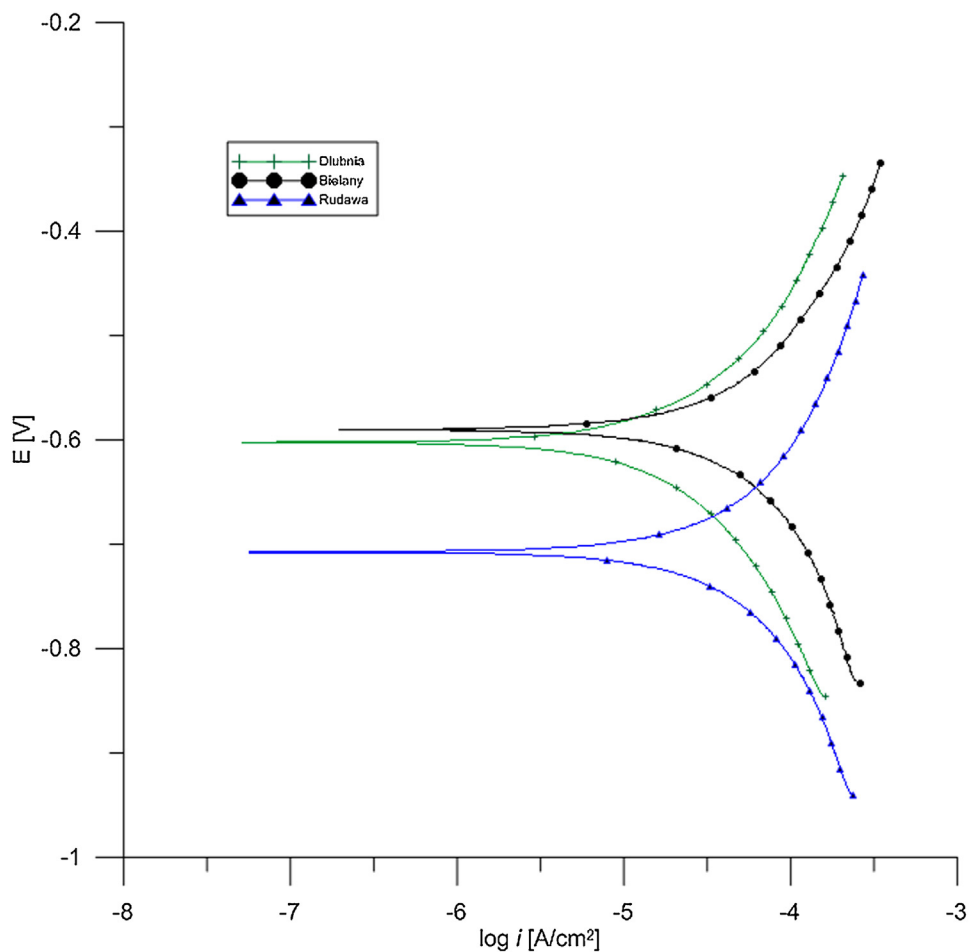


Fig. 3. Graph Tafel polarization curves for carbon steel immersed in Dlubnia, Bielany and Rudawa river waters.

Additionally, increasing air pollution has significant influence due to existence of acid rain phenomena. It will decrease pH of water in the form of wet and dry deposition and content of aggressive agents like sulphuric and nitric acid also it directly or indirectly via runoff from the catchment to river acidity (i.e., depending on characteristics of the surrounding watershed) is variable (Fig. 5).

So, time of collection water sample will strongly affect obtained results in laboratory conditions.

Below are presented impedance spectra obtained for steel sample exposed to water collected from Bielany, Dlubnia and Rudawa rivers after two days of intense rain.

3.2. Flow conditions and oxygen content

Generally, corrosion processes are directly connected with the occurrence of oxygen in water; however, the presence of aggressive carbon dioxide affects the poor quality of residue layers, which contribute to the limitation of corrosion. During stagnation episodes, values of corrosion potential decrease prominently and consistently. During flow episodes, values increase and reach a quasi-steady state (Fabbricino and Korshin, 2014). Experiments with varying concentrations of dissolved oxygen showed that the decrease of corrosion potential values characteristic for stagnation is likely to be associated with the consumption of dissolved oxygen by the exposed metal. The corrosion potential of iron and its changes during stagnation were sensitive to the concentrations of sulfate and chloride ions (Fabbricino and Korshin, 2014). Assuming, it is obvious that corrosion rates of metal exposed in water samples collected in field and transported to the laboratory are affected by the different oxygen conditions and flow conditions. Reproduction of real environmental conditions in laboratory usually is extremely difficult.

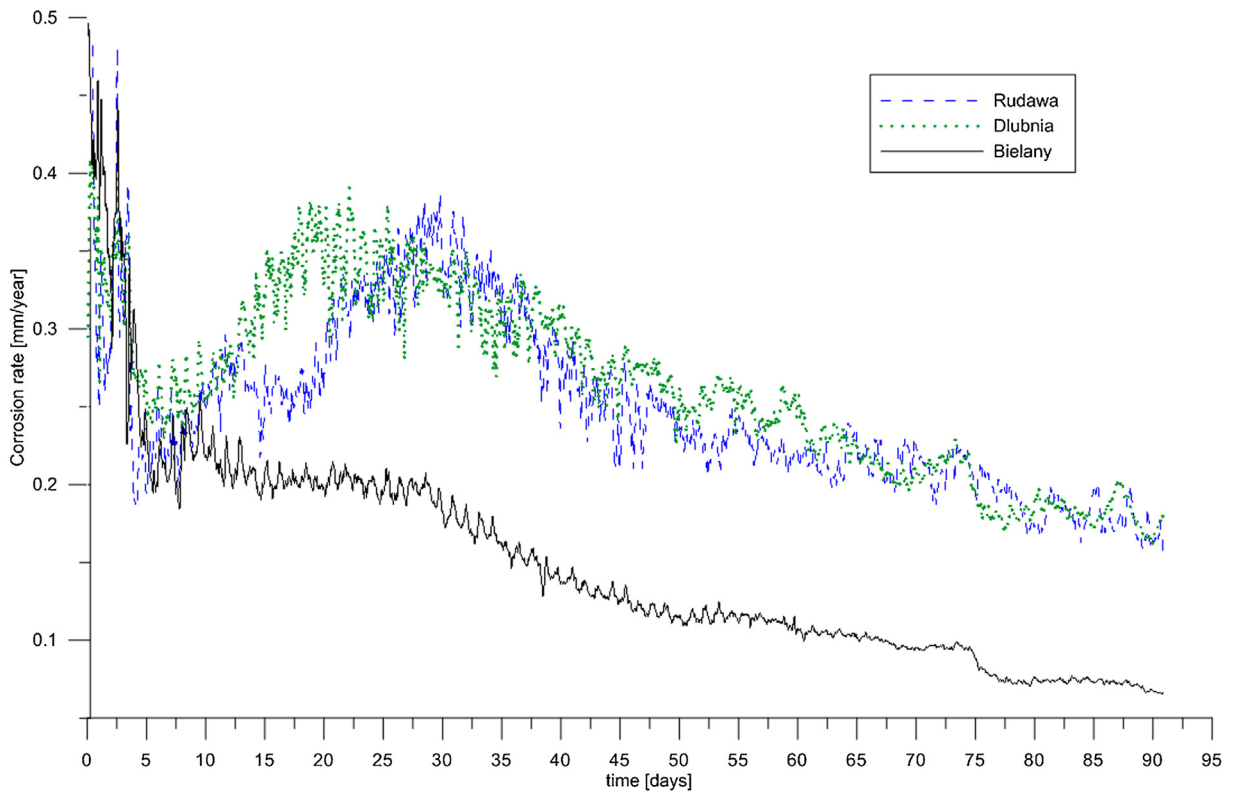


Fig. 4. The results of steel corrosion rates are performed during the first 90 days of steel corrosion rate monitoring.

3.3. Working sample conditions

Using fragment of metal cut from installation as a working sample and sample prepared from the new metal with composition the same as one used in installation, both has some important aspects which can influence obtained corrosion rate by measurements in laboratory conditions.

Most of monitoring systems are applied in installations which are in use already, so the material can be coated with corrosion products. So, fresh metal surface will react differently from the surface with corrosion products on it with environment. However, corrosion products during transport to the laboratory can be oxidized, which can influence both properties of the metal surface and microbial activity.

The influence of existence of corrosion products is clearly visible on Fig. 4. New sensors were installed, so metal surface was on the beginning of exposition free from any deposits. Corrosion rate values from the first 10 days are describing

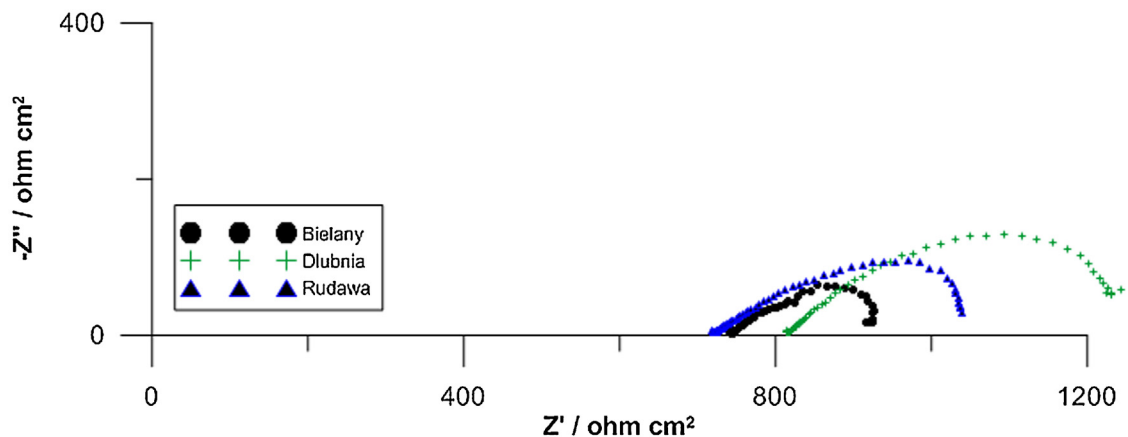


Fig. 5. The Nyquist plots for carbon steel in Bielany, Dlubnia and Rudawa rivers after raining.

conditions were layer of corrosion product is creating. The same situation is represented on Figs. 1 and 2, were laboratory measurements are made on fresh sample. Creation of corrosion product layer visibly reduces corrosion rate by inhibiting access of environment to metal surface. Moreover, as it was said in the introduction part, water supply system in Krakow is based on materials not uniform in their exploitation age. So analysis made in laboratory conditions hardly reproduces actual state of steel in pipeline.

4. Conclusions

On the basis of the research conducted, the following conclusions can be drawn:

- Implemented automatic monitoring systems can significantly reduce number of failures caused by corrosion.
- The results of corrosion rate obtained in laboratory conditions are strictly dependent on the time of sample water collection, the state of working electrode and flow conditions during measurements.
- The corrosivity of water provided from the surface intake cannot be only connected with a change in water temperatures, but also with the oxygen content and other environmental conditions like existence of acid rain or surface run off.
- Monitoring system can provide much more accurate and sensitive to changing environmental conditions results than laboratory measurements.
- A reduction in the corrosion rate improves the quality of water and its chemical parameters fall within the standard range for water intended for consumption.

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References

- Al-Saleh, S.A., 2015. Analysis of total chloride content in concrete. *Case Stud. Constr. Mater.* 3, 78–82.
- Atkins, C., Brueckner, R., Lambert, P., et al., 2015. Field experience of remote monitored and controlled CP systems. *Case Stud. Constr. Mater.* 2, 35–41.
- Bigoni, R., Sorlini, S., Collivignarelli, M., et al., 2014. Drinking water quality assessment and corrosion mitigation in the hospital water supply system of Chacas Village (Peru). *Revista Ambiente & Água* 9, 379–389.
- Cao, D., Xiao, H., Mao, H., et al., 2015. Electrochemical characteristics of n-type GaN in oxalic acid solution under the pre-breakdown condition. *J. Alloys Compd.* 652, 200–204.
- Fabbricino, M., Korshin, G.V., 2014. Changes of the corrosion potential of iron in stagnation and flow conditions and their relationship with metal release. *Water Res.* 62, 136–146.
- Flitt, H.J., Schweinsberg, D.P., 2005. Evaluation of corrosion rate from polarisation curves not exhibiting a Tafel region. *Corros. Sci.* 47, 3034–3052.
- Hoog, N.A., Mayer, M.J.J., Miedema, H., et al., 2014. Stub resonators for online monitoring early stages of corrosion. *Sens. Actuators B* 202, 1117–1136.
- Ishii, K., Boyer, T.H., 2011. Evaluating the secondary effects of magnetic ion exchange: focus on corrosion potential in the distribution system. *Desalination* 274, 31–38.
- Koch, G.H., Brongers, M.P.H., Thompson, N.G., et al., 2005. Cost of corrosion in the United States. *Handbook of Environmental Degradation of Materials, USA, Houston.*
- Mansfeld, F., 2005. Tafel slopes and corrosion rates obtained in the pre-Tafel region of polarization curves. *Corros. Sci.* 47, 3178–3186.
- McCafferty, E., 2005. Validation of corrosion rates measured by the Tafel extrapolation method. *Corros. Sci.* 47, 3178–3186.
- Morgadoa, T.L.M., Sousa e Brito, A., 2015. A failure analysis study of a prestressed steel cable of a suspension bridge. *Case Stud. Constr. Mater.* 3, 40–47.
- Orlikowski, J., Darowicki, K., Jazdzewska, A., et al., 2015. The protection and monitoring of a distribution piping network for potable water supply. *Anti-Corros. Methods Mater.* 62, 400–406.
- Sancy, M., Gourbeyre, Y., Sutter, E.M.M., et al., 2010. Mechanism of corrosion of cast iron covered by aged corrosion products: application of electrochemical impedance spectrometry. *Corros. Sci.* 52, 1222–1227.
- Slepski, P., Gerengi, H., Jazdzewska, A., et al., 2014. Simultaneous impedance and volumetric studies and additionally potentiodynamic polarization measurements of molasses as a carbon steel corrosion inhibitor in 1M hydrochloric acid solution. *Constr. Build. Mater.* 52, 482–487.
- Stern, M., Geary, A.L., 1957. Electrochemical polarization. I. A theoretical analysis of the shape of polarization curves. *J. Electrochem. Soc.* 104, 56–63.
- Volk, C., Dundore, E., Schiermann, J., LeChevallier, M., 2000. Practical evaluation of iron corrosion control in a drinking water distribution system. *Water Resour.* 34, 1967–1974.
- Zhang, X.L., Jiang, Zh.H., Yao, Zh.P., Song, Y., Wu, Zh.D., 2009. Effects of scan rate on the potentiodynamic polarization curve obtained to determine the Tafel slopes and corrosion current density. *Corros. Sci.* 51, 581–587.
- Zimoch, I., 2005. The Krakow's water supply system operation in the aspect of water distribution subsystem failures. *International Symposium on Water Management and Hydraulic Engineering, Ottenstein/Austria paper no. IV.11.*