

Corrosion monitoring in drinking water system by the use of (ER) sensors

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Abstract

Variety of different designs of sensors exist for corrosion monitoring. The main principle is based on the change of electrical resistance due to corrosion activity. The main advantage over other types of sensors is the ease of measurement and interpretation. Electrical resistance (ER) sensors allow direct measurement of metal thickness loss and thus enables the estimation of instantaneous corrosion rate. The method is very sensitive and reliable in case of general corrosion and quite limited in case of significantly localized corrosion. The ER probes are quite frequently used in various branches of industry. In the past, researchers from our institution developed and patented (in Slovenia) corrosion sensor which was primarily designed for reinforced concrete structures. Later on, sensors were equipped with data-loggers for wireless transmission of data to the end user. In the last decade extended researches were carried out on these sensors embedded into laboratory size concrete/mortar prisms, but also on sensors immersed into different aqueous solutions.

In the ongoing research, corrosion rate is monitored in the drinking water system, containing ER probes and steel coupons, made from similar steel as ER probes. Coupons were used for gravimetric determination of corrosion rate. It was found that results of corrosion rate measured by ER probes and coupons are comparable. The main advantage of the use of ER probes is non-invasive monitoring of corrosion rate without the need of weighing the coupons since the data acquisition is wireless. The idea for further development of ER probes and their application in water supply system (indoor and outdoor) is to design T-pieces with incorporated replaceable ER probes.

Résumé

Il existe toute une gamme de capteurs destinés à la surveillance de la corrosion. Leur principe de base repose sur la modification de la résistance électrique sous l'action de la corrosion. Le principal avantage de ces capteurs par rapport à d'autres réside dans la facilité du mesurage et de l'interprétation des données qu'ils fournissent. Les capteurs à résistance électrique (RE) permettent de mesurer directement la perte d'épaisseur du métal et permettent ainsi d'estimer instantanément le taux de corrosion. Cette méthode fournit des résultats très précis et fiables en cas de corrosion générale, mais elle reste d'une efficacité assez limitée en cas de corrosion nettement localisée. Les sondes de type RE sont assez fréquemment utilisées dans divers secteurs de l'industrie. Par le passé, des chercheurs de notre institution ont développé et breveté (en Slovénie) un capteur de corrosion conçu à l'origine pour des structures en béton armé. Par la suite, les capteurs ont été équipés d'enregistreurs de données pour permettre la transmission sans fil de données à l'utilisateur final. Au cours des dix dernières années, des recherches approfondies ont été menées sur ces capteurs intégrés dans des prismes de béton / mortier à l'échelle des laboratoires, mais aussi sur des capteurs immergés dans différentes solutions aqueuses.

Les recherches actuelles consistent à surveiller le taux de corrosion dans le système d'eau potable contenant des sondes à RE et des éprouvettes d'acier, un acier similaire à celui des sondes à RE. Les éprouvettes ont été utilisées pour déterminer le taux de corrosion par gravimétrie. Les chercheurs ont constaté que les résultats des taux de corrosion mesurés par les sondes à RE et par les éprouvettes étaient comparables. Le principal avantage de l'utilisation de sondes à RE réside dans la surveillance non invasive du taux de corrosion sans qu'il soit nécessaire de peser les éprouvettes, puisque la collecte de données s'effectue sans fil. L'étape ultérieure du développement de sondes à RE et de leur application dans le système d'approvisionnement en eau (intérieur et extérieur) consisterait à concevoir des pièces en T contenant des sondes à RE intégrées que l'on puisse remplacer.

Zusammenfassung

Es gibt eine ganze Reihe von Sensoren für die Korrosionsüberwachung. Sie basieren im Wesentlichen darauf, dass sich der elektrische Widerstand unter dem Einfluss von Korrosion ändert. Hauptvorteil dieser Sensoren gegenüber anderen ist, dass die gelieferten Daten relativ einfach gemessen und interpretiert werden können. Elektrische Widerstandssensoren (ER-Sensoren) ermöglichen die direkte Messung des Rückgangs der Metalldicke und so die sofortige Schätzung des Korrosionsgrads. Dieses Verfahren liefert sehr präzise und zuverlässige Ergebnisse bei allgemeiner Korrosion, ist jedoch bei ausgesprochen punktueller Korrosion nur begrenzt wirksam. ER-Sonden kommen in verschiedenen Industriezweigen relativ häufig zum Einsatz. In der Vergangenheit entwickelten Wissenschaftler unseres Instituts einen (in Slowenien) patentierten Korrosionssensor, der ursprünglich für Stahlbetonkonstruktionen konzipiert war. Diese Sensoren wurden dann mit Datenaufzeichnungsgeräten ausgestattet, um die drahtlose Datenübertragung an den Endbenutzer zu ermöglichen. Im Lauf der letzten 10 Jahre wurden fundierte Forschungsarbeiten im Labor zu diesen in Beton/Mörtel-Prismen integrierten Sensoren durchgeführt, aber auch zu Sensoren in verschiedenen wässrigen Flüssigkeiten.

Die aktuelle Forschung konzentriert sich auf die Korrosionsüberwachung in Trinkwassersystemen mit ER-Sensoren und Probestäben aus einem ähnlichen Stahl wie die ER-Sonden. Die Probestäbe wurden zur gravimetrischen Bestimmung des Korrosionsgrads verwendet. Die Forscher stellten fest, dass die mit den ER-Sonden und die mit den Probestäben gemessenen Ergebnisse des Korrosionsgrads vergleichbar sind. Der größte Vorteil der Verwendung von ER-Sonden liegt darin, dass sie eine nichtinvasive Korrosionsüberwachung ermöglichen, ohne dass die Probestäbe gewogen werden müssen, weil die Datenerhebung drahtlos erfolgt. Der nächste Schritt bei der Entwicklung von ER-Sonden und ihrem Einsatz in Trinkwasserversorgungssystemen (in Gebäuden und im Freien) wäre die Entwicklung von T-Stücken mit integrierten ER-Sonden, die ausgetauscht werden können.

Key words: drinking water system, metal components, corrosion, corrosion rate, electrical resistance probes

1. Introduction

Irrespective of significant increase in the use of plastic materials, the metals still remain the major constituent material for drinking water installations: pipes, as well as fittings and other accessories. Unfortunately, metals corrode when they are exposed to drinking water [1]. Corrosion activity (rate of corrosion) depends upon the type of metal and physical and chemical composition of water. In general, corrosion activity increases with increasing temperature. In addition, presence of different ions such as Cl^- and S^{2-} also accelerate corrosion processes, especially those of localized nature. Other influencing parameters of water are pH and alkalinity, hardness, conductivity, etc.. All these parameters of water can be measured separately and based on that corrosion activity/condition calculated [2]. However, real corrosion

processes can locally differ significantly due to local conditions variations, which are hard to measure or even detect [3].

In the real structures, the duration of components for drinking water should be 50 years according to valid national and European specification [4]. In the practice it is observed that corrosion problems can start much earlier, many times only a few years after the installation of a new system. Corrosion damage of elements can cause leakage of particular element; this may have influence to the mechanical stability of buildings, especially water leaks in buildings result in enormous material damage. In addition, quality of drinking water due to corrosion can be at the most of examples degraded, in the worst cases the use of water because of corrosive species such as Fe, Zn, Cr, Pb and similar can be dangerous for human health. Additions of disinfectants, both chemical and physical, which are used to kill microorganisms, accelerate corrosion processes. When the chemical disinfection is not continuous, presence of locally increased content of disinfectant can occur, and on such sites increased corrosion rate [5-7].

Among the most used metal materials for drinking water installation, stainless steels are the most resistant to corrosion under such conditions. Based on observation from the practice, galvanized steels and accessories made from the same or similar materials often fail due to corrosion [8].

Regular audit (based on water parameters measurements) of corrosion condition and knowing of corrosion activity of drinking water system is of a great importance. Temporal or overall corrosion activity can be determined based on a monitoring of influencing parameters or by direct measurement of corrosion rate as a loss of metal mass or change in thickness of metal wall.

In the last decade members of our research team developed so called electrical resistance (ER) type of sensors [9-11]. The operating principle is the thickness reduction of the metal conductor due to the corrosion. Consequent increase of its resistance is measured. Material of the conductor must be identical to the steel of the system. The total (cumulative) loss of metal is thus determined directly and no assumptions or models for the corrosion electrochemistry are needed. This is the major advantage of ER sensors compared to other types of corrosion sensors and measurements (e.g. measurement of resistivity, pH, or corrosion potential, etc.).

Sensors were primarily developed for the monitoring of corrosion rate of reinforcement in concrete structures. In this research paper application of these corrosion sensors for corrosion rate monitoring of metal drinking water installation is shown and described.

2. Experimental

2.1. Description of ER sensors

ER sensors applied in the proposed corrosion monitoring system, were developed and patented (year 2008) by ZAG. The sensors are made as Wheatstone bridge arrangement, where two legs are exposed to corrosion environment and two are protected and serve as a reference, Fig. 1. That arrangement ensures temperature compensation and eliminates unknown resistivity of the connecting cable. Variety of metals can be used for conductive leads e.g. carbon steels, stainless steels, copper, etc. The leads can be made very thin (down to 100 μm for steel and 35 μm for Cu).

Thinner leads means more sensitive sensor, however also shorter lifetime; thus, a compromise between sensitivity and sensor life is needed. The corrosion rates lower than 1 μm per year can be measured with that sensor. Due to small size of the sensor (6.5×11.5 cm and thickness of 4 mm) it can be easily installed, and can be furtherly optimised in size to fit into different environments, However there is possibility of significant form-factor reduction (e.g. 5×7 cm).

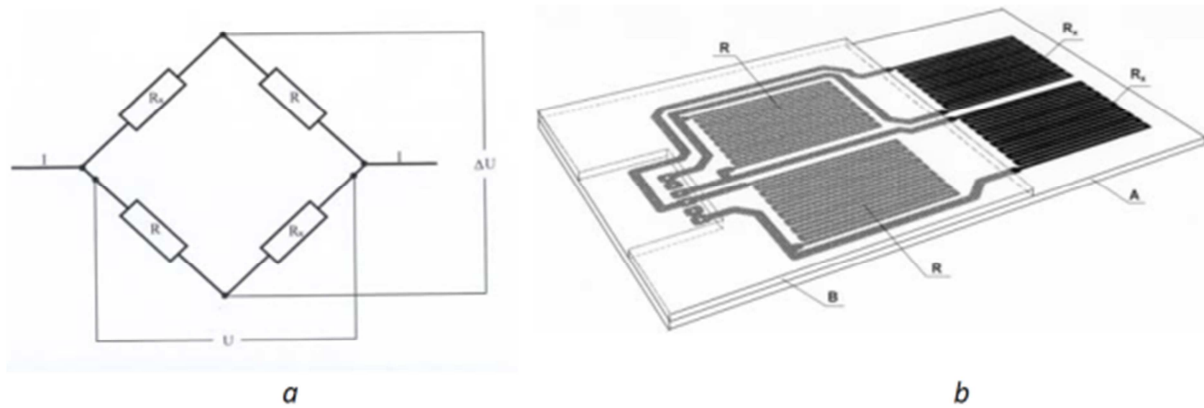


Fig. 1: Sensor circuit (a) and schematic outlook of the sensor (b)

In our current experimental work leads were made from carbon steel on one ER sensor, and from stainless steel on the second ER sensor. The total thickness of leads of ER sensor made from carbon steel was 224 μm , and for that made from stainless steel 91 μm . Chemical composition of steels used for ER sensors construction is presented in Table 1 for carbon steel and in Table 2 for stainless steel.

Table 1: Chemical composition for ER sensor made from carbon steel (all results in mass.%)

Sample identification	% C	% Si	% Mn	% P	% S	% N	% Mo	% Cu	% Pb
sensor	0.0654	0.0088	0.180	0.0250	0.0199	0.0284	0.0099	0.0541	<0.0010
S195T. 1.0026. EN 10255	≤0.20	-	≤1.40	≤0.035	≤0.030	-	-	-	-

Table 2: Chemical composition for ER sensor made from stainless steel (all results in mass.%)

Sample identification	% C	% Si	% Mn	% P	% S	% N	% Cr	% Ni
sensor	0.04	0.50	1.17	0.025	0.003	0.06	18.05	8.04
AISI 304. EN 10088	≤0.07	≤1.00	≤2.00	≤0.045	≤0.015	≤0.11	17.5-19.5	8-10.5

From the chemical analysis it can be seen that carbon steel used for construction of ER sensor corresponding to the qualities commonly used for fabrication of steel pipes. Stainless steel sensors were made from AISI 304 type of steel.

2.2. Experimental procedure

Sensors were exposed to drinking water from Ljubljana water supply system. Results of chemical analysis of water are presented in Table 3.

Table 3: Results of chemical analysis of water

	Unit	Recomended values	Results
pH		6.5-9.5	7.8
Electrical conductivity (20°C)	µS/cm	≤2500	440
Odour	-	-	No odour
Oxidativity	mg/l	<5	<0.5
Total organic carbon – TOC	mg/l	-	0.7
Ammonium	mg/l	<0.5	<0.013
Nitrites	mg/l	<0.5	<0.007
Nitrates	mg/l	<50	13
Sulphates	mg/l	<250	11
Chlorides	mg/l	<250	11
Chlorites	mg/l	-	<0.2
Chlorates	mg/l	-	<0.2
Calcium	mg/l	-	23
Ortho phosphates	mg/l	-	0.74
Phosphorus-total	mg/l	-	1.62
Hydrogencarbonates	mg/l	-	240
Manganese	µg/l	<50	<1.0
Iron	µg/l	<200	<100
Chlorides – free	mg/l	-	<0.02

Both ER sensors were immersed into the same container filled with drinking water. the temperature during immersion was 23±2 °C. In order to simulate fresh drinking water circulation in the system. the water was the entire duration of the experiment bubbled with air. Experimental set-up can be seen on the Figure 2.

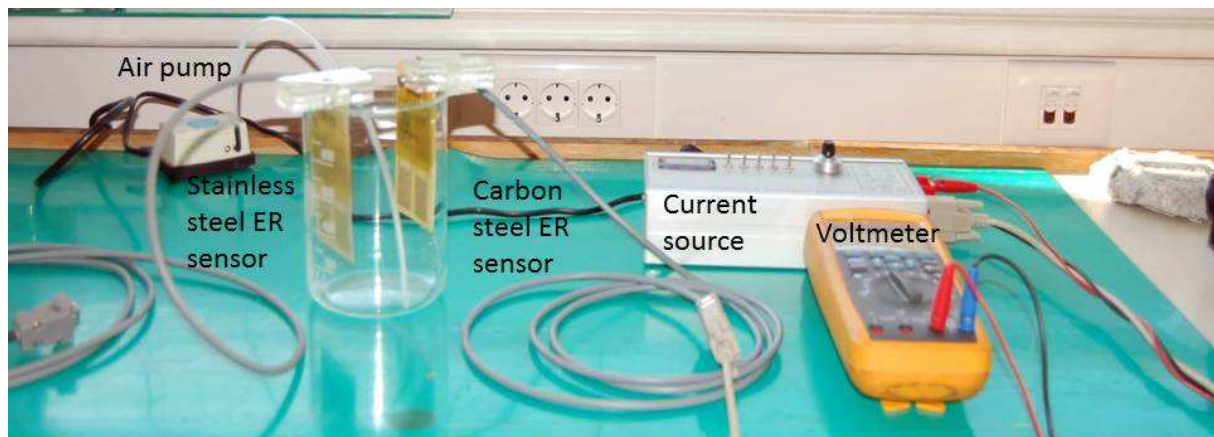


Figure 2: Experimental set-up for measurement of corrosion rate of carbon steel and stainless steel in drinking water

The whole duration of the experiment was 35 days. On 6th and 7th day of exposure. 0.1 g/L of IZOSAN®. commonly used chloride based disinfectant, s. was added into water in the container in order to simulate chemical shock of drinking water system. Evaporated water was replaced regularly.

Data were collected twice per day. After the data (U and ΔU . in mV) were obtained. instantaneous thickness as well as corrosion rate were calculated.

After the experiment was finished. ER sensors were cleaned in order to remove corrosion products and visually examined subsequently.

3. Results and discussion

Graph on the Figure 3 presents the change of the thickness of carbon steel and stainless steel ER sensors during 35 day exposure to drinking water. In the first few days of exposure in drinking water no change of total thickness of sensors was observed, which means no change in corrosion rate.

After 6 days of exposure of sensors in drinking water. 0.1 mg/L of IZOSAN®. In order to simulate chemical shock in the form of sodium hypochlorite. was added to the water. Addition of such concentration of disinfectant caused sudden and intensive corrosion of carbon steel ER sensor resulting in reduction of the total thickness (Figure 3) and increased corrosion rate (Figure 4). Visual examination of the surface of carbon steel ER sensor has shown presence of voluminous corrosion product on the surface (Figure 5). Addition of IZOSAN® did not make any changes on the thickness of ER sensor made from stainless steel or change in corrosion rate of that sensor. On the surface of this sensor no corrosion was observed at that time.

The same concentration of IZOSAN® was added later twice - during the 7th and 9th day of exposure. These additions did not change significantly corrosion behaviour of the sensors.

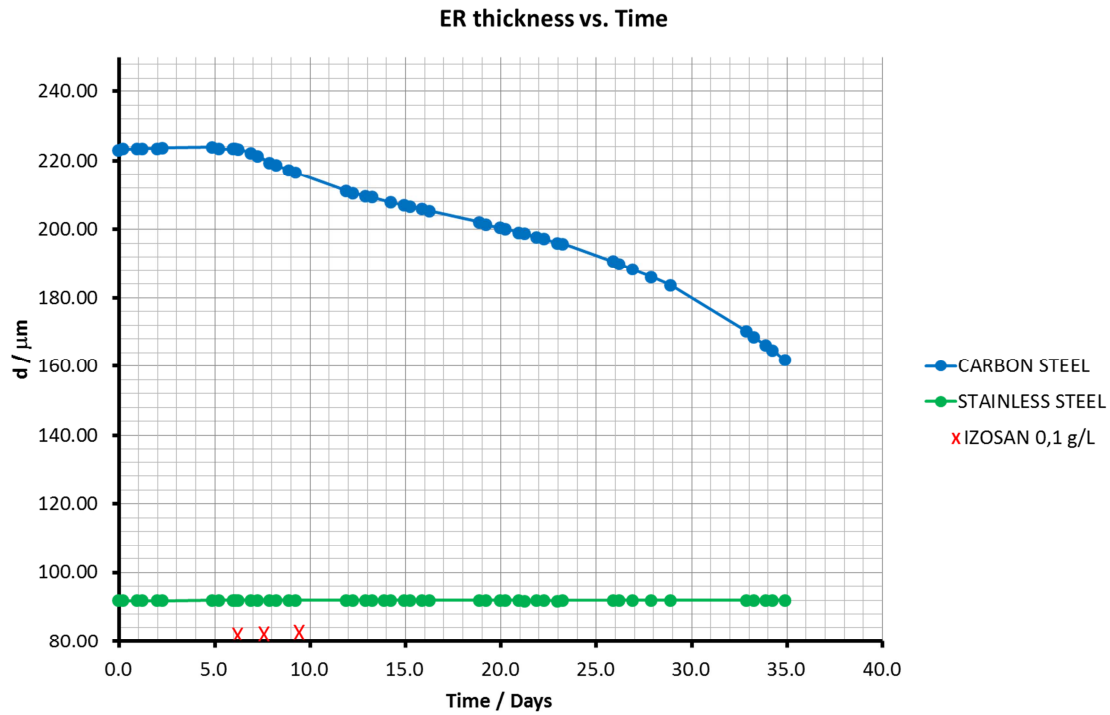


Figure 3: Total thickness change vs. time for ER sensors from carbon steel and stainless steel

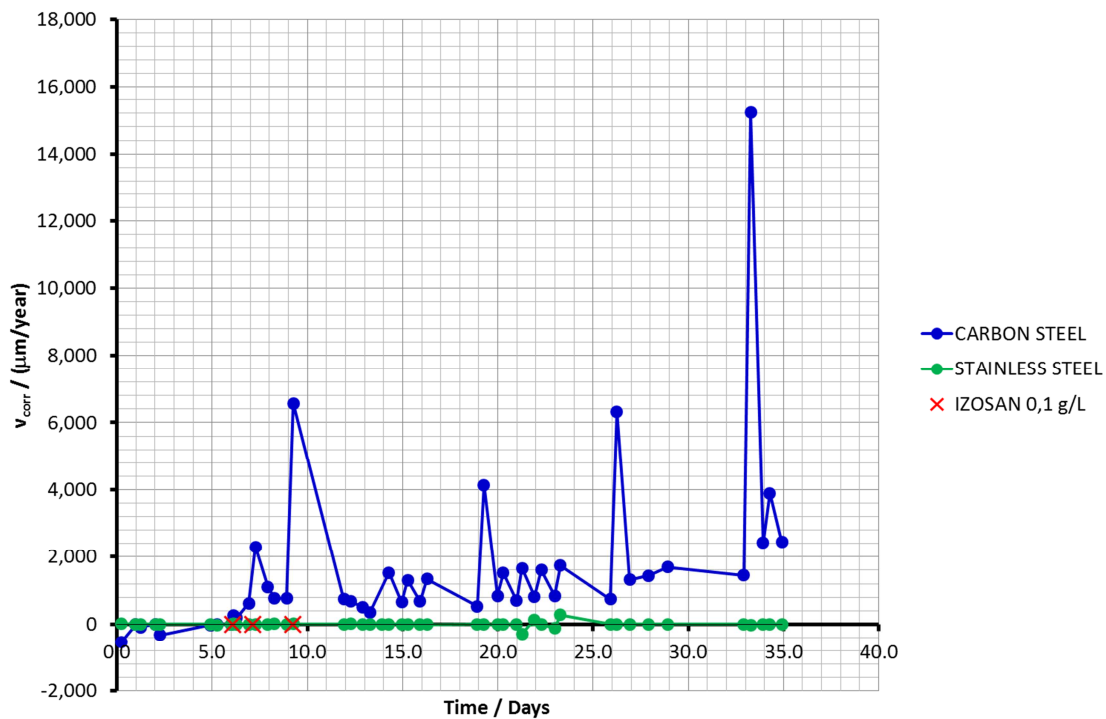


Figure 4: Corrosion rate of carbon- and stainless steel ER sensors vs. time

From graph of carbon steel ER sensor thickness reduction it can be observed that the thickness decreased in 30 days of exposure (from the first addition of IZOSAN®)

from 220 μm to 160 μm . Such reduction means approximate corrosion rate of 730 $\mu\text{m}/\text{year}$. Corrosion rate for stainless steel stayed is estimated to around 1 $\mu\text{m}/\text{year}$. After 35 days of exposure, both ER sensors were removed from water and visually examined. Comparison of the surfaces after 6 and 35 days of exposure can be seen on Figures 5 and 7 for carbon steel and Figures 6 and 8 for stainless steel, respectively. Corrosion products on carbon steel have grown locally – they appeared in few hours after disinfectant was added into water. After that time they expanded only a little. However, from measurements of thickness loss, as well as from visual (Figure 9) and microscope examination (Figure 10) of the surface of steel leads under corrosion products, it was observed how extended corrosion damage is. On the other hand, corrosion sensors made from stainless steel did not shown any larger corrosion damage on the surface. Only small spots of reddish-brown corrosion product were found on the surface (Figure 8), which are very probably sediments of corrosion products coming from carbon steel into water and from water by movement to the surface of stainless steel sensor. Namely, measurements of thickness of ER sensor made from stainless steel did not shown reduction within this exposure.

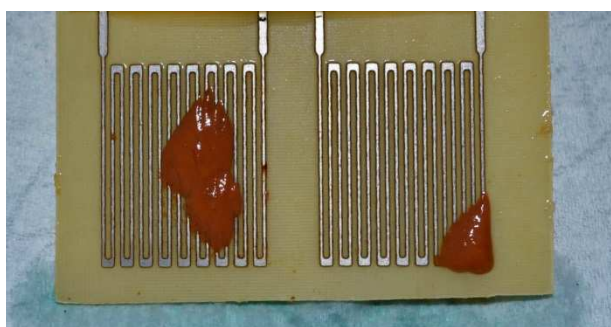


Figure 5: ER sensor from carbon steel after addition of 0.1 mg/L of IZOSAN® (6th day of exposure)

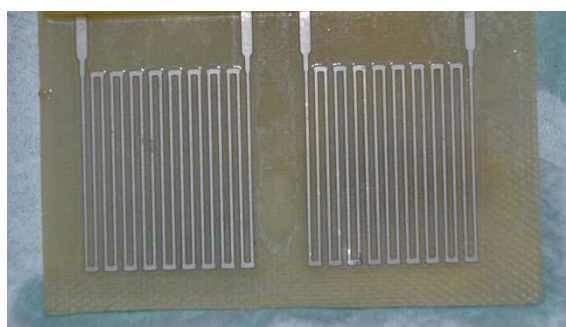


Figure 6: ER sensor from stainless steel after addition of 0.1 mg/L of IZOSAN® (6th day of exposure)

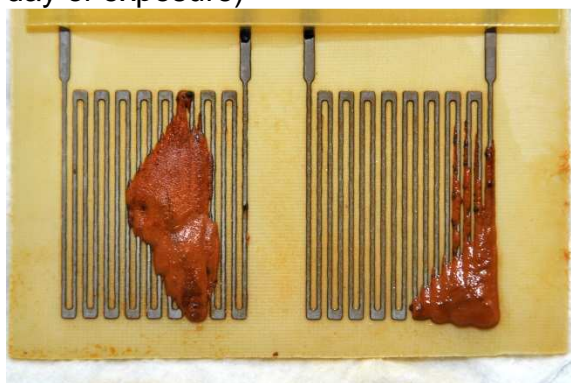


Figure 7: ER sensor from carbon steel after addition of 0.1 mg/L of IZOSAN® (35th day of exposure)

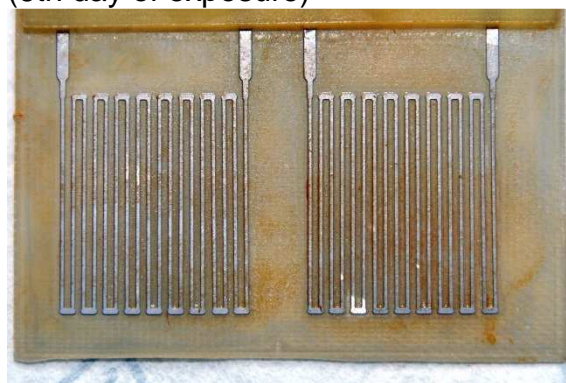


Figure 8: ER sensor from stainless steel after addition of 0.1 mg/L of IZOSAN® (35th day of exposure)

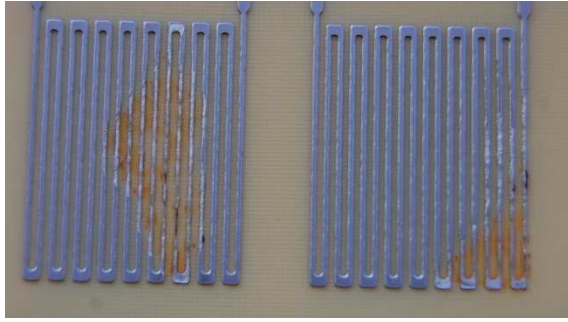


Figure 9: Chemically cleaned ER sensor from carbon steel after 35 days of exposure

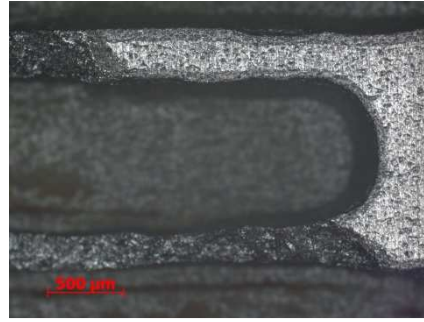


Figure 10: Micro-examination of carbon steel lead of a ER sensor after chemical cleaning (after 35 days of exposure)

From the results of measurements of thickness change and corrosion rate of ER sensors it can be seen that this type of monitoring can reliably detect initiation and propagation of corrosion processes. Corrosion processes of unprotected carbon steel exposed to aerated drinking water are very fast. Corrosion activity strongly depends on the presence of disinfectants. Corrosion rates of carbon steels under such condition could go up to 1 mm/year. ER sensor made from 250 μm thick leads would fail due to corrosion in a few months. Therefore, sensors made from carbon steel can be used only to detect initiation of corrosion in the system to warn the owner. However, corrosion rates so high, or unstable materials, are not an appropriate choice for drinking water systems.

On the other hand, corrosion of stainless steels which are the most resistive metals for drinking water system can be monitored by such system during for longer periods. Initiation of corrosion, even when it appears in localized form, can be successfully monitored in the same way as for carbon steel ER sensor. Since sensors made from stainless steel are thinner, the resolution of measurements is even better.

4. Application to drinking water system

ER sensors are widely used for monitoring of rebar corrosion in reinforced concrete structures. Before the application in the real structure, detailed studies of sensors performance were carried out under laboratory condition and reliability of data obtained was validated by different comparison methods.

Our recently proposed solution is a web-based turn-key corrosion monitoring system for ER sensors made from different materials (so far three types of metals were well studied in this application: carbon steel, stainless steel and copper). In the near future it is planned to design ER sensors with reduced size in order to incorporate them into T-piece which will be replaceable in drinking water system. T-piece with incorporated ER sensor in the system will be connected to data-logger that wirelessly transmits data to an aggregation unit. From there the data are sent via internet to the group of corrosion experts or owner (manager) of system, which will have a real time view of corrosion condition of the system. Schematic representation of the components and information path are given in Figure 11.

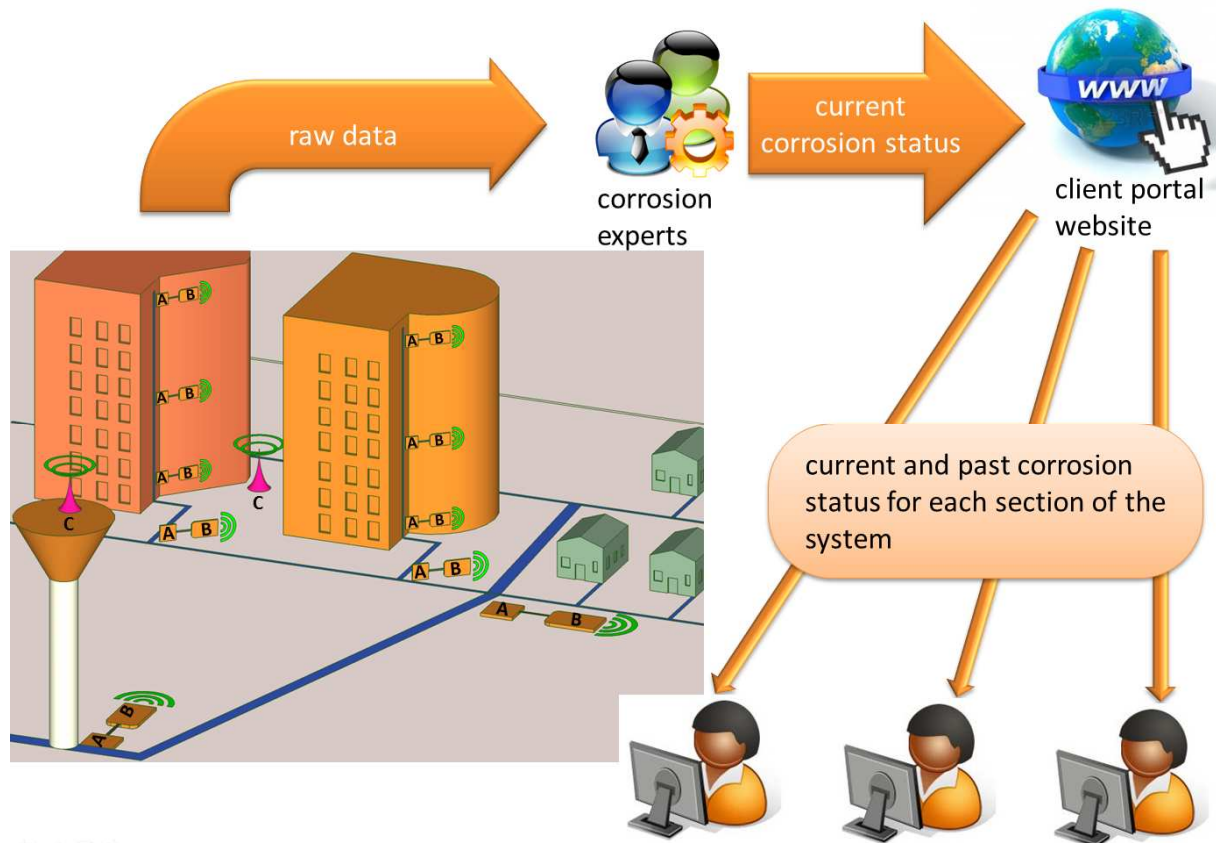


Figure 11: Schematic representation of the corrosion monitoring system.

Corrosion sensors (A) can be installed during the construction phase, during repair or maintenance or whenever else by simple replacing of T or some other standardized type of piece. Each ER sensor is connected to its data-logger (B) by a cable (max length of 20 m, shielded cable 50 m). It is battery powered (average lifetime 5-10 years) and has several functions: signal conditioning and acquisition, data storage to built-in non-volatile memory and bi-directional wireless communication with the aggregation unit. Battery status can be inspected by wireless communication as well. Aggregation unit (C) wirelessly communicates with all data-loggers and aggregates measured data. Maximum distance between data-loggers and aggregation unit is 200 m. This range can be increased up to 10 km with repeaters or more powerful antennas. Aggregation unit has internal memory for data storage and connection to the internet via cable or GSM modem. All acquired raw data are promptly transferred to the server at safe location & duplicated. In case of the internet connection downtime or wireless communication fault, no data are lost and prescheduled measurements continue. Aggregation unit is dedicated for stand-alone operation and has internal and external controller that triggers reset when necessary.

User (expert, structure manager/owner) has an authorized access to the Client portal website where a graphical dashboard with current and past corrosion status for the structure along with structure data is presented. This comprises corrosion rate & metal thickness loss that are automatically generated from each set of measurement data.

5. Conclusions

Corrosion of metals in drinking water system is a severe problem which causes deterioration of the system and also affects the quality of drinking water. In order to keep this under control, periodical control of water quality should be performed. Commonly used microbiological and chemical analyses of water are time consuming and expensive procedure, the result obtained can show only overall condition of drinking water system. By using electrical resistance sensors, the initiation and location of corrosion processes can be detected, in addition, corrosion rates can be estimated.

The main advantages of using corrosion sensors accompanied with data-loggers and user friendly system for analysis in drinking water systems are:

- Complete control of corrosion activity in the system with critical sections without physical presence and without destructive interventions,
- Use for corrosion activity monitoring inside of pipes and fittings, and also outside the system (e.g. in soils, under insulation, etc.),
- Long lasting sensors (corroded sensors could be easily replaced by new).

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