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DEGRADATIONS OF REINFORCED CONCRETE STRUCTURES DUE TO D.C. AND A.C. STRAY CURRENTS

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Lucrarea prezintă rezultatele privind degradările unor probe de beton armat expuse la polarizare în curent continuu (catodică şi anodică) şi în curent alternativ (c.a.). Prin polarizare anodică şi în c.a. probele sunt degradate prin dezalcalinizare şi dizolvarea unor compuşi chimici ai betonului. In consecinţă se produce o scădere substanţială a rezistivităţii electrice şi apar tensiuni interne.

Probele supuse la polarizare catodică intensă au prezentat crăpături adânci în beton, datorită probabil reducerii chimice a unor constituenţi oxidici, proces cu contracţie de volum. Deşi alcalinitatea betonului nu se micşorează substanţial, rezistenţa la întindere prin despicare a betonului armat scade ca rezultat al formării crăpăturilor. Din comparaţia probelor cu polarizare anodică şi polarizare în c.a. s-a găsit o comportare similară; totuşi degradarea în ansamblu a fost mai scăzută în cazul polarizării în c.a.

This paper presents the results of physical and chemical degradations of some reinforced concrete samples exposed to d.c. (cathodic/anodic) and a.c. polarization. By both anodic and a.c. polarization the samples are degraded by de-alkalinization and dissolution of some chemical compounds. Substantial decreases in electrical resistivity as well as occurrence of internal strength tensile are noticed.

Samples subjected to the extended cathodic polarization showed deep cracks, probably due to the chemical reduction of some oxidic constituents, a process with volume contraction. Although the concrete alkalinity does not decreases substantially the overall strength tensile of the reinforced concrete drops as a result of the appearing cracks. By comparing samples with the extended anodic polarization and with a.c. polarization similar behavior was noticed; however, the overall degradation in the case of the a.c. polarization was slower.

Keywords: reinforced concrete, stray currents, anodic and a.c. polarization

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1. Introduction

The degradation of reinforced concrete structures is a complex theoretical issue with great practical importance. The complexity is arising from the physico-chemical characteristics of the concrete and also from the many accelerator factors of degradation which can be of natural origin (climatic factors, humidity, microbiological, earthquakes, etc.) or anthropogenic origin (atmospheric, soil or water pollution, electromagnetic pollution due to d.c. and/or a.c. stray currents, mechanical vibrations). Practical importance of these influences results from the fact that the damage of reinforced concrete structures determines diminution of sustainability and reliability of construction.

A good concrete is a composite with low electrical conductivity, *i.e.* high electrical resistivity ($\rho \approx 100\Omega\cdot m$ or more [1]), which would suggest that its degradation is not influenced by electrical fields. However, in practice as a result of simultaneous action of environmental and biological factors the porosity of concrete increases, and this porosity may lead to moisture retention and substantial decrease of electrical resistivity. Indeed, the greater sensitivity to electric fields associated with a strong degradation of reinforced concrete structures was observed in many cases, especially due to increased intensity of stray currents generated by disturbing electric fields [2÷6].

The aim of this paper is the study the degradation of reinforced concrete under the action of d.c. or a.c. stray currents. The experiments are focused on determining the changes of physical parameters (electrical resistivity, mechanical strength) and chemical parameters (pH and content of Ca, Mg, Al, Fe as well as Cl^- and SO_4^{2-} ions) of reinforced concrete samples immersed in a moderate aggressive solution (0.1% NaCl) together with d.c. polarization (anodic and cathodic) or a.c. polarization of reinforcement steel rebars.

2. Experimental part

The cylindrical samples were made of reinforced concrete prepared by pouring a C20/25 class wet concrete around smooth carbon steel rebars (OB37 steel [7]) having 10 mm diameter and compacted it by vibration [8]. For each sample, the concrete was prepared by mixing for 15 min the following amounts: 300 g cement (CEM II BM (S-V) 32.5R, Holcim, Romania [9]), 1600 g standard sand (EN 197.1/2000 and ISO 679/1989, provided from Soc. Nouvelle du Litttoral, France) and 180 cm^3 demineralizated water. After casting, the samples were kept in water for 7 days and afterwards were maintained in air for maturation 21 days at room temperature, 22ºC.

The inner steel rebars in samples thus prepared were electrically insulated at one end with epoxy resin and were connected with a copper wire at the other end for performing the polarization in electrolytic cell. A photo of the samples prepared for the electrochemical experiments is presented in Fig. 1.

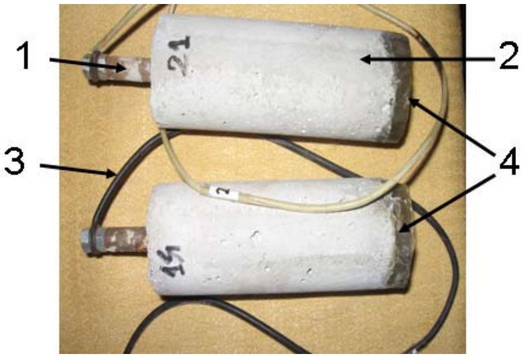


Fig. 1. Reinforced concrete samples made by mixing cement, standard sand and water: 1 – steel rebar; 2 – concrete; 3 – copper wire; 4 - epoxy resin insulation.

In order to simulate the concrete structures degradation by stray currents in heavily polluted environments, the following test procedures were applied:

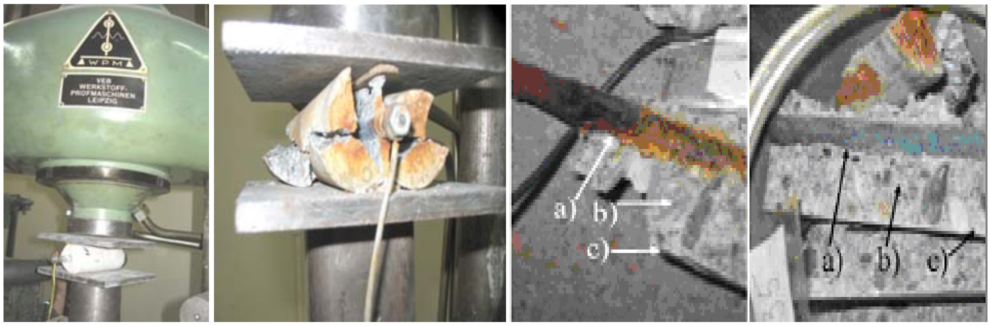
– immersion and storage for 22 days without polarization, in 0.1% NaCl solution;
– anodic polarization in 0.1% NaCl solution (11 days);
– cathodic polarization in 0.1% NaCl solution (22 days);
– a.c. polarization in 0.1% NaCl solution (22 days).

For applying d.c. and a.c. polarization (in galvanostatic regime), a DC regulated power supply PS3003 type (from HQ Power^{TM}) and a.c. electrical source (home made) were used, respectively.

The evolution in time of electrical resistivity, tensile resistance (mechanical strength) by splitting, alkalinity and chemical composition of concrete was determined.

The mechanical resistance tests were performed by using a setup WPM VEB WERKSTOFF-PROFMASCHINEN (Leipzig – Germany) appropriate for destructive determination by splitting [10], illustrated by the photos in Figs. 2a and 2b. Figs. 2c and 2d show various places where samples were prelevated in order to determine the pH value of concrete and also its chemical composition. Three places, marked with **a**, **b** and **c** in both last figures, correspond to the proximity of the steel rebar, the middle of concrete layer and the external surface of splitted concrete, respectively.

For pH measurements, an amount of 1-2 grams of dry concrete powder were mixed with 20 cm^3 of distilled water. After 4 hours of storage at room temperature (23±2°C) the pH was determined using a JENWAY 350 pH-meter. Also, pH determinations were made by classical procedure used in civil engineering, namely, by dripping an indicator solution of phenolphtalein onto the surface of wet concrete and watching the colour change. There were no significant differences (differences were less than 0.3 pH units) between the pH values obtained by the two methods.



(a) (b) (c) (d)

Fig. 2. The determination of the mechanical resistance by splitting (Fig.2a), the recovery of residual concrete (Fig.2b) and the places (Figs. 2c and 2d) for prelevation of samples from the marked areas: **a** -the proximity of the steel; **b -** the middle of concrete layer; **c -** the outer surface of splitted concrete.

In order to determine the chemical composition, dried and weighed amounts of concrete powder were introduced in a hot 63% HNO_3 aqueous solution, in the excess, for 6 hours. The filtered extract as a liquid phase was brought into a flask diluted with distilled water and was analyzed by using an atomic absorption spectrometer SPECTRA A VARIAN 120; thus, the contents in solution of Ca, Mg, Al, Fe, SO_4^{2-} and Cl^- were determined.

Given the heterogeneity of concrete, all determinations were made in triplicate, the samples being subjected to identical treatments; the results were therefore averaged arithmetically.

3. Results and discussion

It is evidently that after long time electrochemical treatment of the immersed concrete samples these underwent significant changes in their physico-chemical properties. Both cases of anodic polarization (in d.c.) and a.c. polarization have produced a roughness of concrete surface together with a color changes (from light brown to dark brown); the occurrence of large and deep cracks and even holes in concrete body was noticed. The photos in Figs. 3 and 4 show some examples of the damages of these samples.

As observed from Fig. 3, after anodic polarization of reinforced concrete with d.c. current for 11 days, the concrete degradation by anodic dissolution of some its constituents is obvious. On the other hand, due to the steel rebar corrosion inside the sample an expansion of internal mechanical stress took place

[11], leading to cracking and peeling of the concrete (detail of Fig. 3), this aspect being often found in practice. A similar behavior, but on a lower extent, is seen at the samples polarized in a.c. current (Fig. 4).

(a) (b)

Fig. 3. (a) The appearance of three reinforced concrete samples exposed to anodic polarization ($3mA/cm^2$ for 11 days). (b) a detail evidencing the formation of deep cracks.

Fig. 4. The appearance of reinforced concrete sample exposed to a.c. polarization ($3mA/cm^2$ for 11 days)

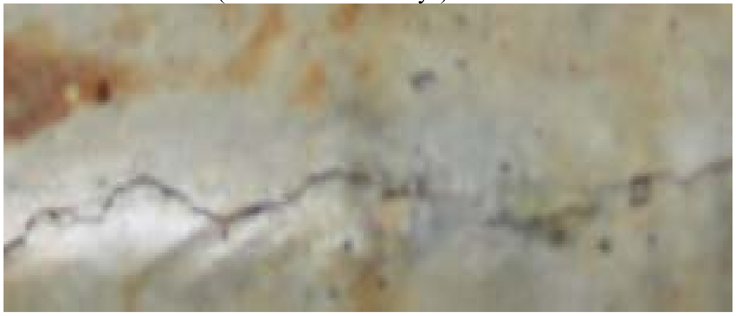


Fig. 5. The appearance of reinforced concrete sample exposed to cathodic polarization ($3mA/cm^2$ for 11 days)

By analyzing the aspect of the cathodic polarized samples (polarized with d.c. current) some longitudinal cracks in the concrete were evidenced (Fig. 5), which can be explained by structural modifications appeared in oxidic bulk of concrete after the long and intensive cathodic treatment.

The behavior in time of the bulk electrical resistivity of the reinforced concrete, maturated and tested to various polarization treatments is presented in Fig. 6. From this Fig. one can find out that after long time under d.c. polarization with both anodic or cathodic currents, and also under a.c. polarization, the bulk electrical resistivity of concrete decreases substantially, unlike the samples only stored in ambient atmosphere (taken as reference). The improved electrical conductivity demonstrates once again the structural changes occurring inside the concrete. The data suggest that this behavior favors, at a given disturbing electric signal, the stray currents to pass easier in the concrete bulk and to increase their intensity in time, thus producing more substantial corrosion damages.

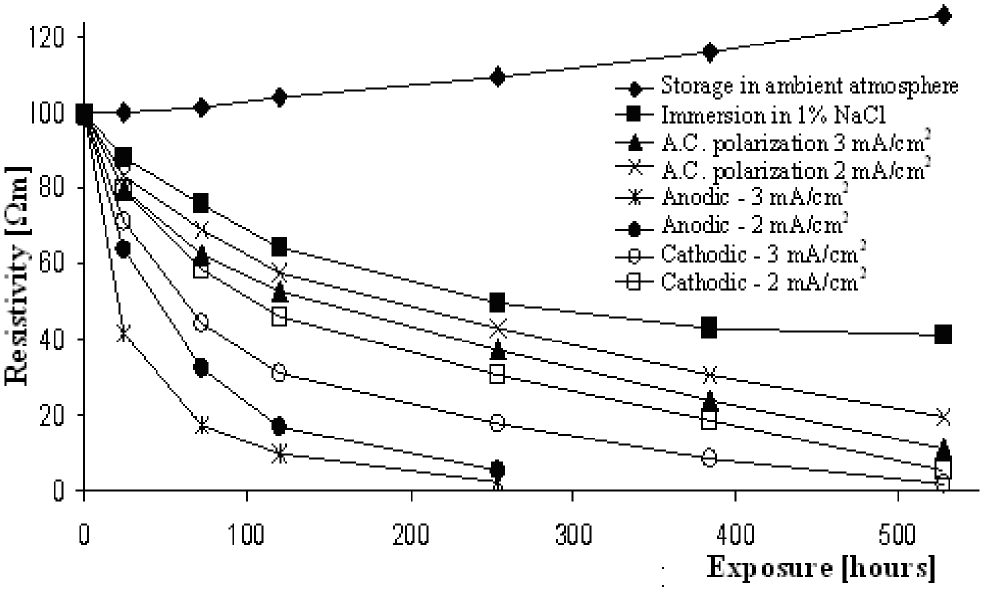


Fig. 6. The comparative evolution of bulk electrical resistivity of reinforced concrete samples subjected to different polarization treatments

The evolution in time of mechanical properties from tests by sample splitting is showed in Fig. 7.

The data presented in Fig. 7, show also that the mechanical strength tested by splitting of reinforced concrete exposed to degradation by stray currents decreases appreciably. It is worth to note this considerable degradation of mechanical strength by comparing with metallic structures, where damages are less evidenced. This may happen mainly because of excessive polarization (with either d.c. currents or a.c. currents) of reinforcement rebars. On the whole, the results of electrical and mechanical damages presented in this paper are in good agreement with [4÷6] and our previous observations in practice regarding the corrosion of buildings, bridges, subway tunnels, structures for energy transportation and distribution etc., damages due to electromagnetic pollution (stray currents) [12÷14].

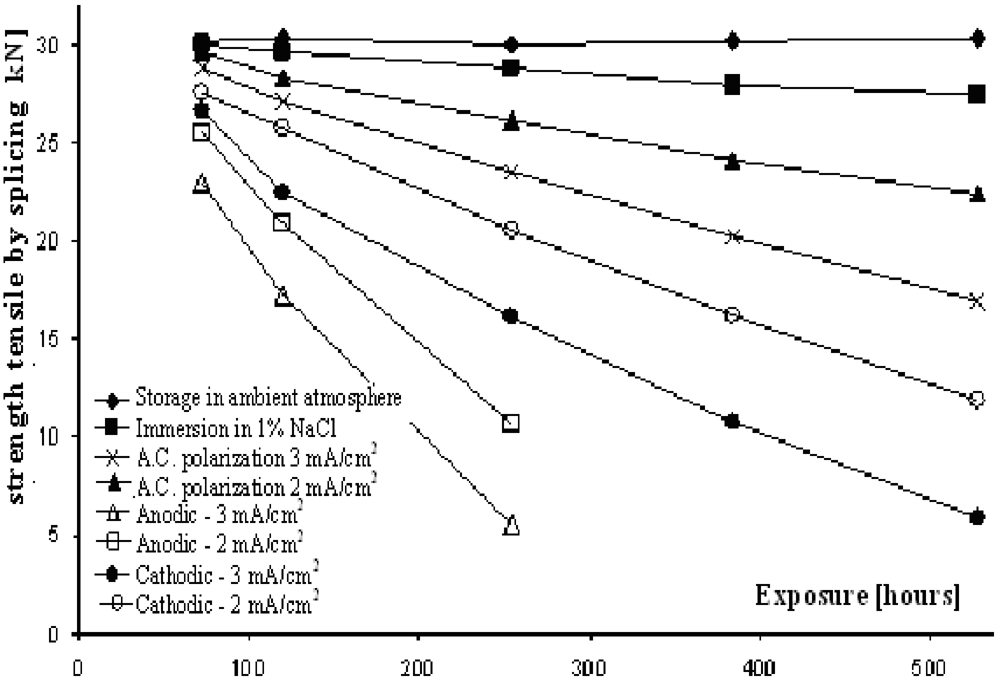


Fig. 7. The comparative evolution of strength tensile by splitting of reinforced concrete samples subjected to different polarization treatments.

A further discussion refers to the results of pH and chemical composition changes obtained using the concrete samples subjected to various electrochemical treatments; the data after 22 days of polarization are presented in Table 1.

By analyzing pH data from Table 1 one may notice that the samples simply immersed for 22 days in NaCl solution or polarized cathodically have a slight dealkalinization (generally with a maximum one pH unit), whereas the anodic polarization of concrete has produced a dramatic dealkalinization. Thus, starting from pH 12.7 the pH values decrease up to pH 6-7 and even pH 1.9 at the external surface of concrete samples. Similarly, the concrete samples polarized with a.c. current exhibit a pH decrease but in a smaller extent (a minimum value of pH 8.9 for external surface).

The evolution of chemical composition also presented in Table 1 shows a non-variable content of SO_4^{2-} ions during the applied electrochemical treatments in all situations. For concrete samples simply stored for 22 days in NaCl solution only an increase in chloride ions content was recorded, certainly due to penetration of ions from chloride solution environment. The samples subjected to cathodic polarization have also no significant modifications in analyzed metal ions content; however, probably due to negative polarization, one notices in this case a slight decrease in Cl^- ion content.

Table 1

The evolution of alkalinity and chemical composition of concrete samples subjected to various polarization treatments

Applied treatment	**Prelevation place**	**pH**	**Content [wt. %] in:**					
			Ca	Mg	Al	Fe	**Cl^-**	**SO_4^{-2}**
Blank sample – stored in air	a)-Fig. 2	12.6	10.85	1.633	2.631	2.317	0.122	0.35
	b)-Fig. 2	12.7	10.80	1.642	2.626	2.321	0.123	0.36
	c)-Fig. 2	12.6	10.89	1.632	2.632	2.313	0.117	0.35
22 days storage in 0,1% NaCl solution	a)-Fig. 2	11.9	10.71	1.631	2.628	2.352	0.155	0.34
	b)-Fig. 2	11.2	10.55	1.624	2.630	2.332	0.176	0.35
	c)-Fig. 2	10.3	10.05	1.602	2.629	2.317	0.266	0.33
11 days anodic treatment with 2mA/cm^2	a)-Fig. 2	7.8	9.48	1.614	2.607	3.451	0.351	0.34
	b)-Fig. 2	6.6	9.42	1.606	2.593	3.387	0.527	0.35
	c)-Fig. 2	1.9	7.52	1.576	2.433	2.359	0.969	0.34
22 days cathodic treatment with 2mA/cm^2	a)-Fig. 2	12.6	10.87	1.635	2.641	2.325	0.117	0.36
	b)-Fig. 2	12.8	10.82	1.642	2.733	2.317	0.109	0.34
	c)-Fig. 2	12.9	10.87	1.652	2.642	2.320	0.107	0.35
22 days a.c. polarization with 3mA/cm^2	a)-Fig. 2	11.7	10.51	1.639	2.677	2.671	0.153	0.36
	b)-Fig. 2	9.2	9.97	1.621	2.574	2.408	0.282	0.35
	c)-Fig. 2	8.9	9.66	1.588	2.566	2.371	0.320	0.35

Concrete samples subjected to anodic polarization for long time exposure have a strong modification in the chemical composition (except for SO_4^{2-}), namely a decrease of in Ca, Mg and Al content in the bulk; on contrary, the concrete body seems to be enriched in Fe species, especially in regions near steel rebars, indicating the occurrence of corrosion; an increase in Cl^- content is also observed. The same behavior, *i.e.* a decrease in the Ca, Mg and Al content and an increase in Fe and Cl^- content was recorded for the samples polarized with a.c. current, but in a smaller extent.

Given the above discussion, we consider that detailed studies on theoretical calculation / modeling [4, 15, 16] of the effect of stray currents in order to reduce their action are necessary to be performed and their importance to substantiate predictive diagnostic studies [3, 17-19] and life time calculations for the reinforced concrete structures is justified.

4. Conclusions

The novelty of this paper consists in the experimental determination of damages due to stray currents (applying both d.c. and a.c. polarizations) for some reinforced concrete samples. The results showed that after long time immersion (more than 530 hours) in 0.1% NaCl solution the electrical resistivity decreases in general at about one half of its initial value, unlike the electrical resistivity of the samples stored in atmospheric air where a small increase (about 20%) was noticed.

Also, the anodic polarization (in d.c.) and a.c. polarization produced a roughening together with color changes (from light brown to dark brown) of the concrete surface; the occurrence of large and deep cracks and even holes in concrete body was also noticed. Both aggressive polarizations led to an excessive corrosion of reinforcement rebars and a significant decrease in electrical resistivity and mechanical resistance of concrete samples. Regarding the chemical changes in concrete bulk, it is remarked a significant decrease in either pH or in Ca, Mg, Al species content, but an increase of iron and chloride ions content. All chemical changes were explained by effect of stray currents.

The cathodic polarization of samples did not show visual surface modifications, although thin longitudinal cracks appeared and a decrease of electrical resistivity and mechanical strength was recorded. It is mentioned that pH and Ca, Mg, Al, Cl^- and SO_4^{2-} contents did not suffer modifications in this case.

It is considered that the experimental data reported in this paper have a great importance to substantiate predictive diagnostic studies and life time calculations for the reinforced concrete structures exposed to stray currents generated by electromagnetic fields.

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