EVALUATION OF EFFECTIVENESS OF CONCRETE COAT AS A STEEL BARS PROTECTION IN THE STRUCTURE - GALVANOSTATIC PULSE METHOD

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Abstract

Early steel bars corrosion in reinforced concrete elements are difficult to detect because of the lack of visible changes on the concrete surface. To assess reinforcement corrosion risk level without structure damage some non-destructive diagnostic methods are applied. One of them is the galvanostatic pulse method. This semi-non-destructive electrochemical method allows to determine the corrosion areas and estimate the steel bars corrosion activity. Using this method it is possible to measure some electrical parameters (corrosion current density, stationary potential and reinforcement concrete cover resistivity) that allow to indirectly estimate the reinforcement corrosion progress in concrete. So far this method has been generally applied to bridges. The article presents results of studies in which the galvanostatic pulse method was used to determine reinforcement corrosion risk in structures elements different than bridges. Two types of reinforced concrete columns were tested under different environment conditions and two groups of laboratory specimens which were subjected to freezing and thawing cycles in NaCl solution or stayed in natural air-dry conditions. The apparatus GP-5000 GalvaPulseTM was used. Based on the obtained results the conclusions were drawn. The galvanostatic pulse method allows to assess the progress of the reinforcement corrosion process in tested elements. However, it is necessary to measure simultaneously all parameters and make their complex analysis.

Keywords: Steel bar, reinforcement corrosion, non-destructive test method, laboratory test, filed test

1. INTRODUCTION

Reinforced concrete elements used for many years under various conditions have different degree of destruction. Elements subjected to the direct weather impact and unprotected from it are subjected to the degradation faster than the others. The most dangerous are carbon dioxide from the air and dissolved in water chlorides. These factors, compounded by changes in temperature and humidity, as well as mechanical damage, lead to destruction of concrete coating (cover) and facilitate reinforcement corrosion [1-6]. Because of the carbon dioxide and the physical - chemical processes effect the concrete carbonation appears. As a result of carbonation the concrete pH gradually decreases and the neutralized concrete areas reach deeper into the structure up to reaching the passive layer. The concrete protective role is due to its highly alkaline pH ($pH \approx 12.5 \div 13.5$). At $pH < \sim 11.8$ passive layer is destroyed and the electrochemical reinforcement corrosion can appear [1-4]. Sometimes, however, it may lead to the reinforcement corrosion development also at pH greater than 11.8. The most common reason of this type destruction are chlorides, which in the form of ions dissolved in the water penetrate the pores of the concrete structure and lead to local pitting [1-3]. In both cases: in the carbonation process or due to chloride penetration, external damage of concrete coating may be invisible while the reinforcement corrosion can be significant [1,5]. On the other hand concrete coating may be damaged as a result of mechanical interactions. This type of damage is often visible but it doesn't mean that reinforcement corrodes [5,6]. Therefore the research methods that allow to determine the reinforcement corrosion risk in concrete elements without removal concrete coating (cover) are very significant [7,8]. One of these methods is non-destructive galvanostatic pulse method. So far this method has been generally applied to bridges [5,9]. The article presents results of studies in which this method was used to determine reinforcement corrosion risk in structures elements different than bridges. The main research objective was to assess the effectiveness of the measurements results made in various elements exposed to different environmental conditions [11]. Therefore tests were performed on: laboratory specimens subjected to freezing cycles in the 3 % sodium chloride solution (labeled F), laboratory specimens left in natural air - dry conditions (labeled N), power poles (labeled P) that have been exposed to the real long-term impact of weather conditions [6], internal columns of frame structure (labeled C) exploited under favorable environmental conditions.

2. TEST METHOD

Non-destructive electrochemical research methods were developed taking into account that the reinforcement corrosion process in concrete is an electrochemical process running in the electrolyte and the oxygen presence supply [2,8]. The electrolyte in this case is concrete with pores filled with an alkaline liquid and the reinforcing rod disposed is the electrode. Using the galvanostatic pulse method it is possible to measure some electrical parameters [8,10] that allow to estimate the reinforcement corrosion progress in concrete indirectly. The electrical parameters are: reinforcement stationary potential, concrete cover resistivity and the corrosion current density. The reinforcement stationary potential measurements and concrete cover resistivity are the basic measurements [2,8], which allow only point out areas where conditions for corrosion are more favorable. These measurements are not very accurate [6,12]. More reliable are so-called advanced measurements [2,8], consisting of additional corrosion current density measurement so we can estimate the reinforcement corrosion activity and forecast its rate [2,8,10]. One of the few devices which are designed for measuring the polarization is the GP-5000 GalvaPulse^{TM} set [10]. This set allows to perform basic measurements or advanced. The main set elements are: control and recording device, silver-chloride reference electrode and calibration device. The apparatus is accompanied by information about the test results interpretation criteria (**Table 1**) [10].

Table 1 The criteria for assessing the reinforcement risk corrosion degree [10]

Criteria for assessing the degree of reinforcement corrosion risk				
Advanced measurements	Basic measurements	Reinforcement stationary potential, E_{st} (mV)	> -200	5 % of corrosion probability
			-350 ÷ -200	50 % of corrosion probability
			< -350	95 % of corrosion probability
		Concrete cover resistivity, Θ (kΩ·cm)	≥ 20	small corrosion probability
			10 ÷ 20	medium corrosion probability
			≤ 10	high corrosion probability
	Corrosion current density, i_{cor} (μA / cm^2)		< 0.5	not forecasted corrosion activity
			0.5 ÷2.0	irrelevant activity corrosion
			2.0 ÷ 5.0	low corrosion activity
			5.0 ÷ 15.0	moderate corrosion activity
			> 15.0	high corrosion activity

3. LABORATORY AND FIELD TESTS

3.1. Laboratory specimens research

There were 12 rectangular specimens with dimensions 210 × 228 × 100 mm made. All specimens were made of concrete C40/50. As reinforcement were used two parallel bars (BST 500) with a diameter of 8 mm placed in intervals 70 mm from the specimens edges side. The concrete coating was 25 mm. All specimens were made in a laboratory with constant humidity and temperature (air-dry conditions). The research to assess the reinforcement corrosion risk in the specimens was carried out in two stages. The first stage started 3 months after the specimens concreting. In all specimens there were measurements made in accordance with the GP-5000 GalvaPulse^{TM} set requirements [10]. For each specimen orthogonal grid of four measuring points was determined (two points above each bar), where the stationary potential, concrete cover resistivity and corrosion current density were measured. These results allowed to obtain reference values for the later measurements. After that specimens were divided into two groups:

- group A (6 pieces, Numbers F1 ÷ F6); these specimens were subjected to 120 freezing and thawing cycles in 3 % sodium chloride (NaCl) in order to initiate chloride corrosion on the reinforcement,
- group B (6 pieces, Numbers N1 ÷ N6); these specimens were left in natural laboratory air-dry conditions.

After specimens' freezing cycles the second stage of measurements was made. For all specimens, in pre-designated points, the advanced measurements were performed. Obtained results (**Tables 2.1 ÷ 2.3**) were analyzed based on the criteria given in **Table 1** [10].

Table 2.1 The corrosion current density measurement results

Specimen Nº		corrosion current density, i_{cor} ($\mu A / cm^2$)							
		stage I (initial measurements)				stage II			
		point 1	point 2	point 3	point 4	point 1	point 2	point 3	point 4
group A	F1	1.08	1.07	1.25	1.19	4.27	4.22	4.86	3.63
	F2	1.74	1.17	1.48	0.96	6.37	6.59	6.12	6.37
	F3	1.31	1.16	1.20	0.98	6.78	5.01	6.54	4.90
	F4	1.15	1.05	1.00	1.07	5.46	6.08	2.60	2.54
	F5	1.04	1.08	0.86	1.24	6.23	4.87	4.98	5.10
	F6	1.07	0.95	1.12	1.18	7.93	6.07	3.96	3.56
group B	N1	0.63	0.58	0.64	0.62	0.36	0.25	0.46	0.29
	N2	0.77	0.83	0.73	0.99	0.38	1.11	0.37	0.51
	N3	1.29	1.36	1.12	1.29	0.41	0.31	0.44	0.35
	N4	0.92	1.01	1.03	0.99	0.44	0.39	0.42	0.55
	N5	1.51	1.02	1.15	1.02	0.74	0.60	0.53	0.57
	N6	1.63	1.07	1.38	1.02	0.59	0.59	0.48	0.43

Table 2.2 The reinforcement stationary potential measurements results

Specimen Nº		reinforcement stationary potential, E_{st} (mV)							
		stage I (initial measurements)				stage II			
		point 1	point 2	point 3	point 4	point 1	point 2	point 3	point 4
group A	F1	-230	-217	-226	-223	-218	-232	-141	-203
	F2	-178	-210	-201	-214	-189	-203	-253	-188
	F3	-228	-319	-224	-239	-299	-295	-221	-320
	F4	-168	-275	-165	-262	-220	-221	-224	-212
	F5	-150	-156	-257	-249	-282	-341	-288	-335
	F6	-174	-246	-180	-247	-271	-254	-266	-252
group B	N1	-35	-31	-34	-17	-84	-55	-120	-69
	N2	-51	-63	-262	-263	-10	9	-123	-94
	N3	-217	-224	-326	-327	-109	-67	-132	-92
	N4	-123	-121	-234	-225	-128	-125	69	70
	N5	-166	-172	-221	-209	-125	-123	-124	78
	N6	-199	-256	-213	-259	-116	-130	-180	-220

Table 2.3 The concrete cover resistivity measurements

Specimen Nº		concrete cover resistivity, Θ (kΩ·cm)							
		stage I (initial measurements)				stage II			
		point 1	point 2	point 3	point 4	point 1	point 2	point 3	point 4
group A	F1	1.2	1.2	1.1	1.1	1.9	1.8	1.8	2.4
	F2	1.2	1.3	1.2	1.3	1.3	1.4	1.4	1.5
	F3	1.4	1.4	1.3	1.2	1.5	1.4	1.6	1.7
	F4	1.3	1.2	1.2	1.2	1.0	1.2	1.0	1.3
	F5	1.3	1.2	1.3	1.2	1.1	1.1	1.0	1.2
	F6	1.3	1.2	1.2	1.2	1.0	1.2	1.1	1.2
group B	N1	1.4	1.5	1.5	1.4	26.5	22.2	29.2	27.2
	N2	1.4	1.2	1.3	1.3	34.0	24.9	18.2	16.2
	N3	1.3	1.3	1.2	1.1	28.2	23.2	23.9	22.8
	N4	1.4	1.3	1.3	1.2	22.1	26.3	22.1	28.3
	N5	1.2	1.2	1.3	1.2	24.7	23.7	26.6	28.9
	N6	1.3	1.3	1.2	1.1	26.2	26.1	23.5	25.4

3.2. Research of poles

Table 3 The power poles and poles of the building structure measurements results

Pole N°	corrosion current density, i_{cor} (μA / cm^{2})			reinforcement stationary potential, E_{st} (mV)			concrete cover resistivity, Θ (kΩ·cm)		
	point 1	point 2	point 3	point 1	point 2	point 3	point 1	point 2	point 3
P 1a	2.25	2.99	5.7	-36	29	-86	6.1	10.5	13.9
P 1b	1.76	21.76	4.6	-41	-81	-72	8.2	14.1	13.5
P 2a	1.63	1.2	0.71	-47	-30	-9	5.8	5.0	7.7
P 2b	1.95	1.47	1.49	-7	-10	-10	3.7	6.4	5.4
P 3a	1.61	0.94	1.06	-61	-4	-29	5.8	7.7	6.3
P 3b	1.25	1.31	0.60	-27	-33	-15	6.0	4.7	4.0
P 3c	1.66	1.26	0.38	-54	-47	-1	5.4	4.8	4.0
C 1a	0.05	0.05	0.04	-141	-96	-108	63*	60*	55*
C 1b	0.09	0.11	0.10	1.87	-89	- 97	26.5	31	21.5
C 2	0.13	0.07	0.08	-126	1.6	-115	34.6	15.6	26.2
C 3	0.10	0.05	0.07	-134	-81	-85	8.9	20.2	23.6
C 4	0.00	0.42	0.04	-144	-49	-99	9.9	24.7	28.9

* results out of the test range [10]

Two types of reinforced concrete poles were tested. The first poles type were exterior poles (labeled P). They were exposed to long-term environmental impact, including in particular the negative atmospheric conditions impact. Poles were reinforced with ribbed bars with 8 mm diameter. The concrete cover (coating) was 8 ÷ 10 mm. Three poles were examined. These elements' the average concrete strength was measured by rebound hammer test and was ~ 37 MPa. The age of poles was estimated at ~ 50 years. The second poles type were reinforced concrete load bearing internal columns (labeled C). The columns' reinforcement was made of ribbed bars with a 20 mm diameter. The concrete cover (coating) was 20 ÷ 25 mm. The four columns were examined. The average concrete pillars strength made by the rebound hammer test was 55 MPa. The age of columns was estimated at ~ 48 years. Electrochemical studies involved the reinforcement stationary potential, concrete cover resistivity and corrosion current density measurements at three measuring points located directly above the main reinforcement and spaced every 30 cm. The research on the rod was made during the summer - the dry season when the ambient temperature was ~ 27 °C. Research on poles was made in the building during the autumn when temperatures inside the building was around 3 °C. All measurements were recorded (**Table 3**) and analyzed on the criteria given in **Table 1** [6,10].

4. ANALYSIS OF THE RESULTS

4.1. Laboratory specimens

The main parameter by which we can determine the reinforcement corrosion progress is corrosion current density. Other parameters are less important - specify only circumstances which can lead to the reinforcement corrosion. Corrosion current density measurement made in the research first stage on 12 specimens indicated that at no point the corrosion current density exceed i_{cor} = 2 μA / cm^{2} which shows negligible corrosion activity (**Table 1**). The obtained results comparison in the study second stage showed that at the points of the specimens A the corrosion current density at 11 points increased significantly reaching i_{cor} = 2.54 ÷ 4.98 μA / cm^2, providing low activity, and at 13 points i_{cor} = 5.00 ÷ 7.93 μA / cm^2, with a moderate corrosion activity. In the specimens B the corrosion current density measurements in both stages remained the same level and do not exceed 2 μA / cm^2 (**Table 2.1**). The reinforcement stationary potential measurements results did not allow for the clear conclusions (**Table 2.2**). In the first measurements stage at the 30 points the stationary potential was lower than -200 mV, (E_{st} = -201 ÷ -327 mV) which indicated 50 % of reinforcement corrosion probability. Only at 18 points these values were higher than -200 mV allowing to estimate the corrosion probability at the level of 5 %. In the measurements second stage at 17 points of specimens A the stationary potential decreased in relation to the measurement in the first stage where in the reinforcement corrosion probability increase may be requested, although the results indicated that it was still at 50 %. In 7 points stationary potential value increased. In 3 points value was greater than -200 mV, indicating low than 5 % corrosion probability. In all points of the specimens B in a second stage measuring the stationary potential values were higher than -200 mV, which indicate the corrosion probability at 5 %. Compared to the measurements made in the first stage at 13 points the corrosion probability was reduced from 50 % to 5 %. The concrete cover resistivity measured values in the first stage at all points of the specimens ranged Θ = 1.1 ÷ 1.5 kΩ·cm (**Table 2.3**). It was much less than 10 kΩ and indicated a high corrosion probability (**Table 1**). In a second measuring stage at the points of the specimens A the parameter value still remained at the same level (**Table 2.3**). However, in the specimens B at 22 points the concrete cover resistivity increased over 20 kΩ·cm, allowing to estimate the corrosion probability as low (**Table 2.3**).

4.2. Poles and columns

The poles have been operated for about 50 years. The study involved power poles that have been exposed to the real long-term impact of weather conditions and internal columns of frame structure exploited under favorable environmental conditions. This element groups choice allowed to compare the results of reinforcement corrosion elements threat operated in extremely different conditions. The testing poles results are described in **Table 3**. They were analyzed based on the same criteria as the specimens [10]. According to the given in [10] nomenclature of corrosion current density obtained from measurements on power poles (results range i_{cor} = 0.38 ÷ 21.76 μA / cm^2) indicated a "high corrosion activity" of reinforcement in the P1b pole (at one point i_{cor} = 21.76 μA / cm^2), "moderate" in the P1a pole (at one point i_{cor} = 5.7 μA / cm^2), and the remaining poles at "insignificant corrosion activity". The same parameter allowed to determine the reinforcement corrosion activity in the frame columns (C1 ÷ C4) as "not forecasted" (results range i_{cor} = 0 ÷ 0.42 μA / cm^2). On the measurements basis of the second parameter, i.e. the reinforcement stationary potential the corrosion likelihood can be drawn about at 5 % in both types of poles. The value ranges results were similar and were as follows: for power poles E_{st} = -86 ÷ 29 mV, and for columns E_{st} = -144 ÷ 1.87 mV. It should be noted that this parameter does not show precisely observed, in fact, the existing differences in the reinforcement wear degree or both types corrosive poles threats (visible reinforcement of poles places were clearly corroded). The concrete cover resistivity value allowed for clearer (but also imprecise) determination of the reinforcement rod condition difference undergoing long-term impact of unfavorable external conditions and poles operated under favorable conditions. The results values for power poles ranged Θ = 3.7÷14.1 kΩ·cm clearly indicated a "medium" (four points) and "high corrosion probability" (most points) of reinforcing bars. The obtained results for columns ranged Θ = 20.2 ÷ 34.6 kΩ·cm indicating a "low corrosion probability" (most points) and range Θ = 9.9 ÷ 15.6 kΩ·cm, providing a “medium corrosion probability” (three points).

5. CONCLUSIONS

1) The galvanostatic pulse method allows to assess the progress of the reinforcement corrosion process in both laboratory specimens and the real elements. However, it is necessary to measure simultaneously corrosion current density, stationary potential and concrete cover resistivity and make complex analysis.

2) Only basic measurements performance (reinforcement stationary potential and concrete cover resistivity) can lead to wrong conclusions.
3) Among the three measured values the corrosion current density is the most reliable measurement.
4) Concrete cover resistivity measurement made on new specimen is not reliable (indicates high reinforcement corrosion probability). This may be related to the physicochemical changes, occurring in young concrete due to the strong surface moisture during the measurements.
5) The reinforcement stationary potential measurement made on new specimens indicates 50 % corrosion probability and in the 50 years old poles 5 % corrosion probability what proves the inaccurate results.
6) Measurements are only possible on a leveled, pure and strongly moisturized concrete surface.
7) The ambient temperature during the measurements can affect the obtained results both for the test piece (heating or strong cooling) and because of the measuring apparatus behavior. Preliminary measurements made on the same laboratory specimens outdoors in the winter (temp. ~ -5 °C) and, immediately after it, in a warm room (temp. ~ 23 °C) showed repeatable and significant differences in the values of all three measured parameters: corrosion current density, the reinforcement stationary potential and the concrete cover resistivity. This research is being continued by authors.

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