Reinforcement Corrosion Degree Effect on Adhesion with Concrete

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A number of aggressive substances influence reinforced concrete building structures' decay and corrosion processes. In this research work the influence of steel reinforcement corrosion degree on its adhesion to concrete strength characteristics was determined. Two 14 mm diameter reinforcement steel types: ribbed (BSt500S) and smooth (A240C) were used in the work. The mass loss of steel reinforcement due to the corrosion was calculated. After the explosion in different solutions: 10 % of NaCl, HCl and NH_4NO_3 the weight of steel reinforcement with smooth surface decreases for 1-8 %, while the mass loss of ribbed reinforcement was 2–13 % in comparison with control of steel reinforcement samples, which exposure in water. It was found that both smooth and ribbed steel reinforcement influenced by NH_4NO_3 solution corroded more intensively. The adhesion of this type of reinforcement (influenced by NH_4NO_3 solution) to the concrete was the lowest: the adhesion of smooth steel reinforcement decreased till 76 % compared to the control concrete specimens adhesion and ribbed steel reinforcement was 92 %. The unaffected steel reinforcement samples adhesion to concrete was the highest (46.33 kN and 59.875 kN, this is corresponds 100 %).The potentiometric measurements showed that the most favorable probability of steel reinforcement corrosion to perform is when the steel reinforcement is exposed to NH_4NO_3 solution, potential difference is < -350 mV.

Keywords: *reinforcement, concrete, corrosion degree.*

1. Introduction

Metals' corrosion is usually defined as degradation of the properties as a result of chemical and electrochemical reaction with environment. Corrosion is a self-contained conversion of metals into raw ores (Ohtsu *et al.,* 2011). The different damages are experienced because of metal corrosion; this problem is relevant for manufacturing production processes (Elgarf,1997).

Reinforced concrete is a widely used building material. The use of steel reinforcement in concrete structures provides more strength and maintains required shape and dimensions of the material, but a number of aggressive substances can affect reinforced concrete building structures' decay and corrosion processes (Yoon *et al*., 2000). The influence of carbonates, sulfates, chlorides and frost-thaw cycles are the main reasons of reinforced concrete structures deterioration. The carbonation processes occurring in concrete structures absorbing CO_2 and moisture, decrease concrete pH and determine corrosion processes in steel reinforcement concrete (Shima *et al.,* 1999, Vidal *et al.,* 2007, Zhang *et al.,* 2010). When the reinforced concrete structures are influenced by sulphates, the former new crystalline structures in concrete significantly increase its volume and this is resulted by various sizes of gaps and cracks (Novak, *et al.,* 2001; Kanakubo *et al.,* 2008; Kayyali and Yeomans,

1995). The chlorides operating in steel reinforcement concrete, destroys oxidized iron passive layer and further the oxidation processes take place intensively. So, it is necessary to protect reinforced concrete structures from the aggressive effects of aqueous solutions, because water is the catalyst of chemical reactions of aggressive components in alkaline concrete environment (Alonso *et al.,* 1998; Imperatore and Rinaldi, 2009; Kurahashi and Oshita, 2009, 2004; O'Brien Corporation, 2004, Alonso *et al.,* 1998).

Mechanical strength of steel reinforcement and concrete adhesion depends on the surface of the reinforcement, physical-mechanical properties of concrete, load direction, stress state, and other factors.

The measurement methods of reinforced concrete qualitative corrosion process, determining the corrosion process and intensity are classified into:

a) visual inspection of the reinforced concrete structure determining the uniformity of corrosion, the nature and the color of corrosion products, their adhesion with metal, etc.;

b) the assessment of the environment, where the reinforced concrete structure corrosion processes take place, i.e., the nature of the sediments, turbidity, etc.;

Table 1. Chemical composition of used reinforcements

Reinforcement steel mark	Chemical composition, %															
	C 100	Si 100	Mn 100	P 1000	S 1000	Cr 100	Ni 100	Cu 100	Mo 1000	V 1000	N_2 1000	C_{eq} 100	N 1000	Ti 1000	B 1000	As 1000
BSt500S	17	20	57	12	32	7	12	26	9	3	9	30	-	-	-	-
A240C	18	8	54	11	44	2	2	2	-	-	-	-	7	5	0,8	5

c) the use of indicators for cathode and anodic areas distribution on the surface of reinforced concrete structures which allows to determine the solution color change.

The weight method is the main quantitative reinforced concrete construction corrosion process determination method. The thickness of corrosive steel reinforcement layer is directly proportional to the sample mass change when corrosion in reinforced concrete structures has continuous and even nature. Corrosion rate K is expressed by the sample mass change per surface area and time unit (Eq. 1) (Vidal *et al.*, 2007):

$$K = \frac{\Delta m}{S \cdot \tau};$$ (1)

where: Δm is the mass change, S is the area; τ is time.

The necessary large number of samples is the disadvantage of steel reinforcement corrosion weight method, as one sample gives only one point of "corrosion rate – time" dependency.

The released or absorbed gas volume during corrosion is measured using volume method for the detection of steel reinforcement corrosion degree. Hydrogen is released during steel reinforcement corrosion processes and hydrogen-depolarization. Oxygen is absorbed if corrosion processes take place in an oxygenated depolarization. Corrosion meter determines hydrogen volume during corrosion. Corrosive steel reinforcement weight is calculated according to the reaction equation when gas volume is known. The volume method evaluates corrosion process kinetics of an individual sample. However, this method is more complicated and is not accurate when corrosion takes place with mixed oxygen–hydrogen depolarization.

The purpose of this scientific research work was to determine the influence of steel reinforcement corrosion degree on its adhesion to concrete and concrete's strength characteristics.

2. Materials and methods

Two 14 mm diameter reinforcement steel types: ribbed (BSt500S) and smooth (A240C) were used in the work. Their chemical composition is given in table 1.

Each reinforcement type was grouped into five groups with three 125 mm long bars. Each group was exposed by different solutions:

- Group 1 was the control group; it was stored under normal (laboratory)conditions;
- Group 2 had water impact;
- Group 3 had 10 % of NaCl solution impact;
- Group 4 had 10 % of HCl solution impact;
- Group 5 had 10 % of NH_4NO_3 solution impact.

All steel reinforcement groups were exposed for six months. Reinforcing steel respectively corroded and the appropriate layer of rust were formed on the surface. Steel exposed to ammonium nitrate solution corroded most of all. The composition of steel corrosion products was determined by XRD analysis. Corrosion product analysis was determined by diffractometer DRON – 6. Note: CuK_a radiation, Ni filter, the detector movement step was 0.02 °, the intensity of the measurement time step was 0.5 s, and tube voltage was 30 kV, the current was 20 mA.

After six months of the exposure in different environments, all types of steel reinforcement samples were embedded in 100x100x100mm size concrete cubes.

Portland cement CEM I 42.5 N (MA) LST EN 197-1 (the specific surface was 310 m^2/kg, setting start was 150 min, the early strength after 2 days was 24.3 MPa, and the standard strength after 28 days was 57.4 MPa) was used.

The composition of the concrete was estimated and C20/25 class samples (table 2) were formed.

Corroded steel reinforcement was embedded in concrete cube center, in an upright position with overhanging 25 mm bar from the cube (Fig. 1). Concrete samples were stored in water for 28 days in order to reach the standard strength. Steel reinforcement from concrete cubes was pushed out after 28 days. The force required to push out the reinforcement from concrete cube, i.e., the force of steel reinforcement adhesion with concrete, was fixed.

Table 2. Composition of $1m^3$ of concrete C 20/25

Materials	The amount of $1m^3$ of concrete mixture, kg
Portland cement	280.0 kg
Water	166 kg
Coarse aggregate (gravel) 4/16 mm fraction	1010.0kg
Fine aggregate (sand) 0/4 mm fraction	850.0 kg
Superplasticizer, Muraplast FK 63.3"	1.4 kg
Water-cement ratio	W/C = 0.59
Density of the concrete	ρ_b =2306 kg/m^3

ToniTechnik 2020.0600/132/02 computerized press was used for measuring the strength of concrete specimens and deformations. Measurement range was 0 ... 600 kN; measurement rate was 0 ... 1.0 N/mm^2×s, load rate was (0.6 ± 0.4) MPa/s.

The device Elcometer 331 was used to measure the probability of reinforcement corrosion in concrete. Copper sulphate electrode was used for potentiometric measurements. Reinforcement corrosion probability was defined when the potential value between the reinforcement bar in concrete and the standard electrode was used.

Fig. 1. Concrete samples with embedded steel reinforcement after the crushing test

3. Results and discussion

Formed on the sample the surface of reinforcement, rust were selected from the smooth and ribbed steel reinforcement groups of samples, which were affected by NaCl, HCl, and NH_4NO_3 solutions. The rust layer was negligible on the other concrete samples that were exposed to H_2O and controls.

According to the XRD it was determined that sodium chloride crystals, iron oxide and iron oxide hydrates dominated in the corrosion products after the steel reinforcement sample treatment by NaCl solution (Fig. 2).

After six months, according to XRD, crystallized ferric chloride dominated in steel reinforcement corrosion products of smooth reinforcement samples exposed to HCl (Fig. 3). Akagenite (ferric chloride, version) and traces of quartz (Fig. 3, a) were detected on ribbed bars near the dominant crystallized ferric chloride.

NH_4NO_3 prevailed in rust of smooth and ribbed steel reinforcement samples, affected by NH_4NO_3 solution. Traces of $Ni(NO_3)_2(NH_3)_6$ were detected in rust of smooth reinforcement. SiO_2 and $FeO(OH)_2$ compounds were find in the corrosion products of ribbed steel reinforcement samples treated with NH_4NO_3.

Steel reinforcement samples were weighed before and after corrosion test in order to evaluate the degree of corrosion more exactly. Determinated weight losses are presented in column diagrams (Fig. 5). The greatest weight losses for corroded smooth and ribbed steel reinforcement
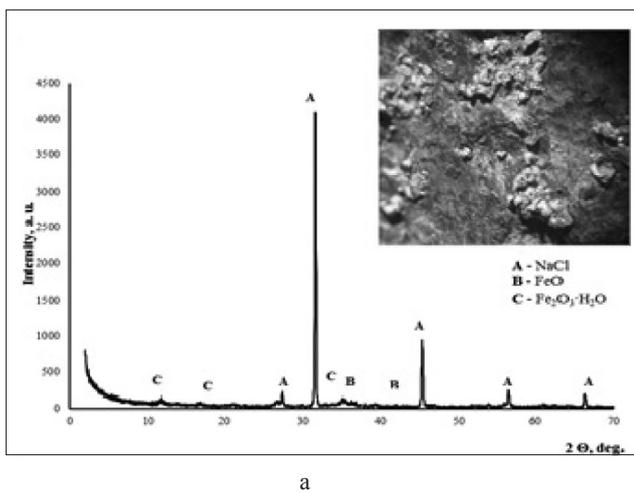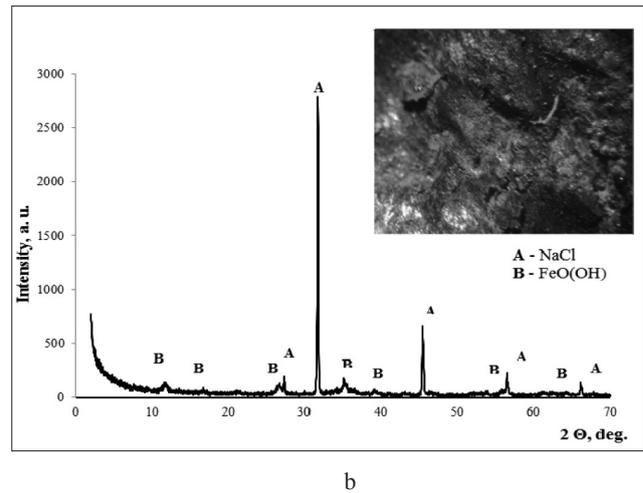
Fig. 2. XRD of smooth (a) and ribbed (b) reinforcements affected by 10% of NaCl aqueous solution
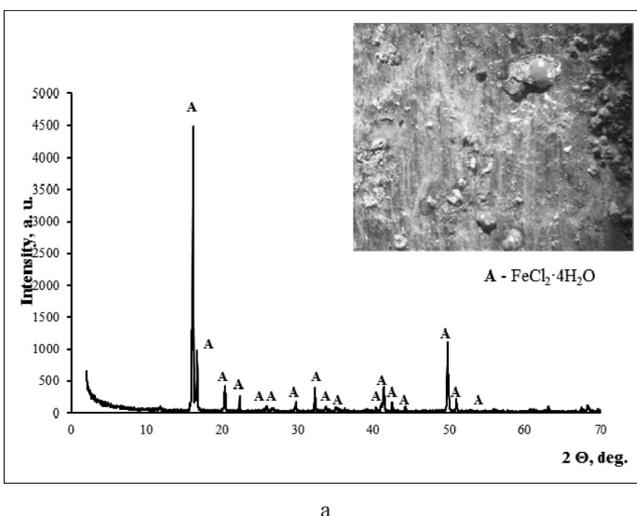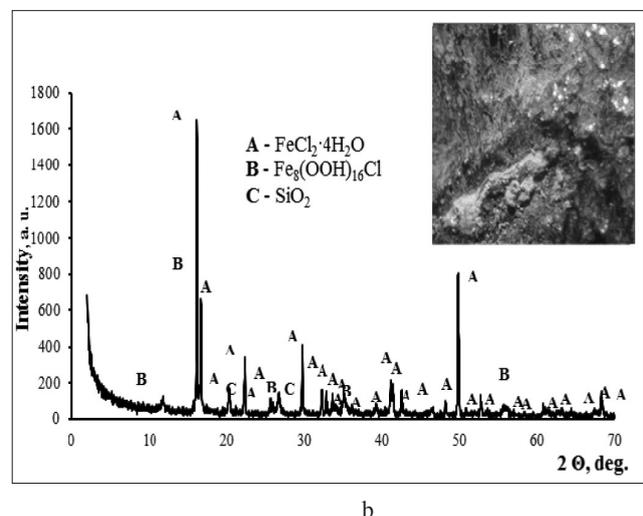
Fig. 3. XRD of smooth (a) and ribbed (b) reinforcements affected by 10% of HCl aqueous solution
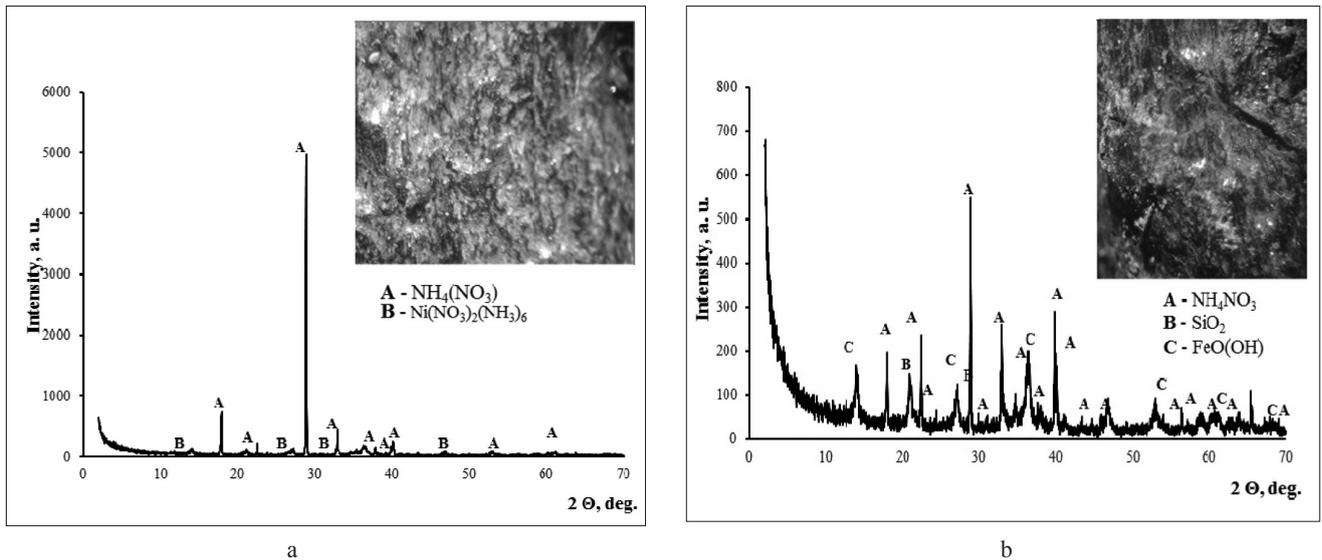
Fig. 4. *XRD of smooth (a) and ribbed (b) reinforcements affected by 10% of NH4NO3 aqueous solution*

were detected for the samples treated with NH_4NO_3 solution. The lowest corrosion degree of steel reinforcement samples were for that samples which held in the air and affect with water (groups I and II).

The corrosion rate (KL) of steel reinforcement was calculated according to the formula (Eq. 2) (ASTM G1-03 1999):

$$KL = \frac{K \cdot W}{S \cdot D \cdot T} \text{ , mm / year;} \qquad (2)$$

where: K is the coefficient, $K = 8.76 \cdot E4$; W is weight loss, g; S is the damaged surface area, cm^2;

$S = 2 \cdot \pi \cdot r^2 + 2 \cdot \pi \cdot r \cdot h$

h – reinforcement length, cm; h = 12.5 cm;
D – metal density, g/cm^3; D = 7.85 g/cm^3;
T – testing time, val.; T = 1.5 year = 13140 h.

Steel reinforcement corrosion degree of testing samples on the next stage was calculated according to the given formula No 2, and the results are presented in table 3. The maximum corrosion rate was in the samples of Group 5, the minimal was in Group 1 of steel corrosion samples.

Steel reinforcement corrosion weight loss products are presented in Fig. 5.

Table 3. *Determination of corrosion degree*

Reinforcement types	Corrosion degree, mm/year	
	Ribbed	**Smooth**
Group 1.	0	0
Group 2.	0.0257	0.0125
Group 3.	0.0521	0.0320
Group 4.	0.0827	0.0653
Group 5.	0.1626	0.0980

Deformation curves of the steel reinforcement samples were determinate as well. Steel reinforcement was squeezed and concrete cube crashed after the overloading of the steel reinforcement samples by compressive load. Sample deformation and load dependence is curved, the deviation from the straight line increases with increasing load and stress. Concrete test cubes were loaded with a constant load. The test data are presented in Fig. 6.

The minimum force of steel reinforcement adhesion to the concrete was set in the samples of Group 5. Ribbed steel reinforcement adhesion force of this group decreased by 92 %, and smooth reinforcement decrease was 76 % in comparison to the control samples (Group 1) adherence force.
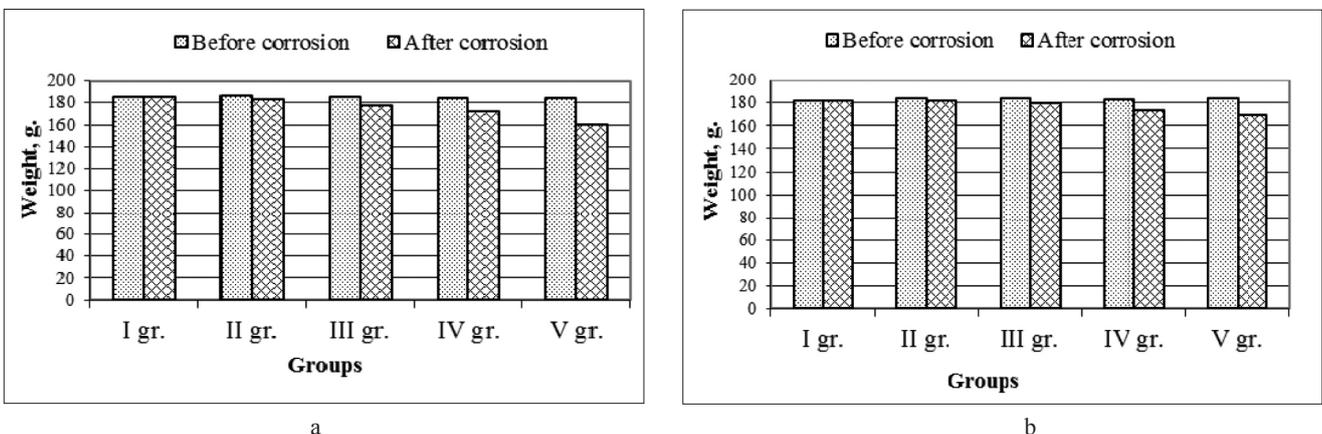
Fig. 5. *Steel corrosion weight loss of smooth (a) and ribbed (b) reinforcement after 6 months*
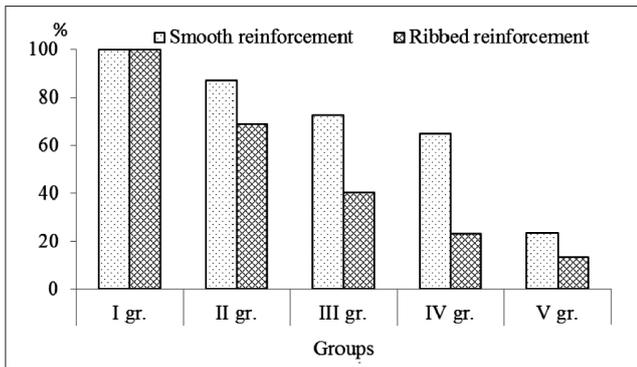
Fig. 6. The relative force changes of steel reinforcement adhesion with concrete

The reinforced concrete samples corrosion conditions predictions dependence on the corrosion time was determined using a copper/copper sulfate electrode (Table 5). Direct potentiometry (Zhang *et al*., 2010) was measured on eight test points as shown in test scheme (Fig. 7).

Table 5. Corrosion criteria in steel reinforcement concrete samples, using a variety of standard electrodes (according to ASTM C876-91)

Copper/copper sulfate electrode; measured potential, mV	Corrosion conditions
> -200	Slight (10 % probability of corrosion)
-200...-350	The medium
< -350	High (> 90 % probability of corrosion)
<-500	Particularly expected

The potential jump, called the electrode potential is formed during electrode and solution contact. Metal cations' transition from the solid phase to liquid or liquid to the solid is the reason of its appearance. The appeared negative charge electrostatically attracts metal cations passed to the solution that are located at the metal negative surface.
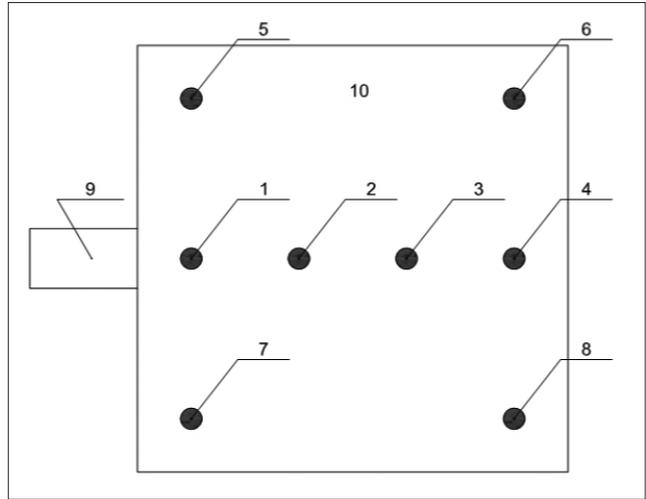
Fig. 7. Corrosion potential measurement scheme: 1–8 points of measurement, 9 – reinforcement, thickness 14 mm, 10 – reinforced concrete cube

The potentiometric measurements showed that the most favorable probability for corrosion is in Group 5, where the steel reinforcement was exposed to NH_4NO_3 solution. The potential difference is equal to -350 mV. However, the corrosion rate is likely to decrease in time (Fig. 8).

Ribbed reinforcement Group 3

Smooth reinforcement Group 3

Ribbed reinforcement Group 5

Smooth reinforcement Group 5
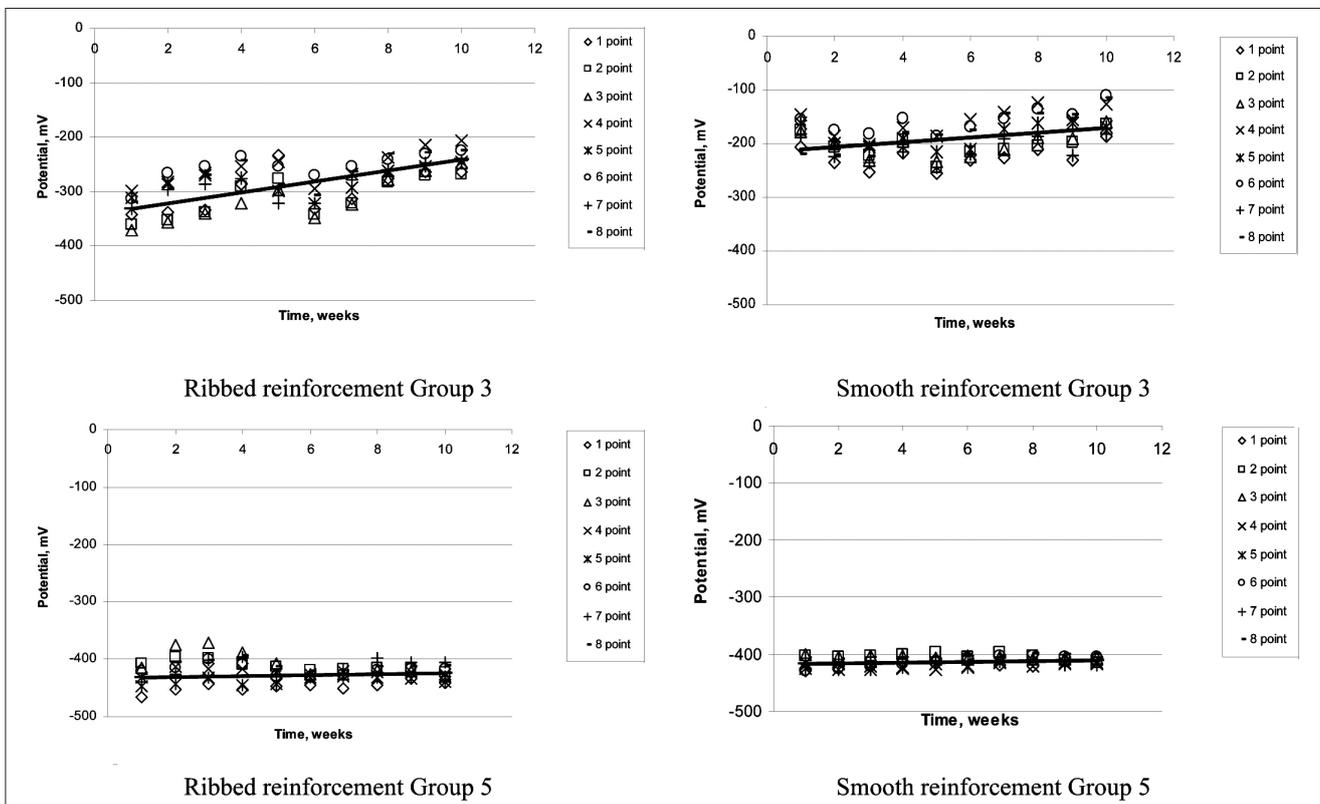
Fig. 8. Corrosion conditions prediction dependence on the corrosion time using copper/copper sulfate electrode in steel reinforcement concrete samples

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The lowest probability for corrosion is in the Group 3, where the steel reinforcement was exposed by NaCl solution, and the potential difference was > -200 mV.

4. Conclusions

1. The mass loss of steel reinforcement due to the corrosion was calculated. After the explosion in different solutions: 10 % of NaCl, HCl and NH_4NO_3 the weight of steel reinforcement with smooth surface decreases for 1–8 %, while the mass loss of ribbed reinforcement was 2–13 % in comparison with control of steel reinforcement samples, which exposure in water.

2. The XRD analysis of all the samples showed that sodium chloride NaCl dominate in the samples of the steel reinforcement corrosion products in Group 3; Ferric chloride crystallized $FeCl_2 \times 4H_2O$ in Group 4, and ammonium nitrate NH_4NO_3 in Group 5.

3. It was found that both smooth and ribbed steel reinforcement influenced by NH_4NO_3 solution corroded more intensively. The adhesion of this type of reinforcement (influenced by NH_4NO_3 solution) to the concrete was the lowest: the adhesion of smooth steel reinforcement decreased till 76 % compared to the control concrete specimens adhesion and ribbed steel reinforcement was 92 %. The unaffected steel reinforcement samples adhesion to concrete was the highest (46.33 kN and 59.875 kN, this is corresponds 100 %).

4. The potentiometric measurements showed that the most favorable probability of steel reinforcement corrosion to perform is when the steel reinforcement is exposed to NH_4NO_3 solution, potential difference is < -350 mV.

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