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INFLUENCE OF THE AIR-ENTRAINING AGENT IN THE CONCRETE COATING ON THE REINFORCEMENT CORROSION PROCESS IN CASE OF SIMULTANEOUS ACTION OF CHLORIDES AND FROST

ABSTRACT

The paper presents the test results to evaluate the effect of air-entraining agent addition on the intensity of reinforcement corrosion in concrete with blast-furnace slag cement in the case of simultaneous action of chloride corrosion and frost. Two groups of reinforced concrete specimens were prepared for the study. The first group of specimens included air-entraining agent addition and the other group was prepared without air-entraining agent. The blast-furnace slag cement (CEM III/A) was used for the specimens. Two parallel reinforcing rods were placed in each specimen. The specimens were subjected to 120 cycles of freezing and thawing in 3% NaCl solution to induce corrosion on the reinforcement. To determine the occurrence of the reinforcement corrosion and estimate the corrosion activity the non-destructive electrochemical galvanostatic pulse method was used. On each specimen the corrosion current density of the reinforcement was measured as well as the reinforcement stationary potential and the concrete coating resistivity, i.e. values indicating the ongoing reinforcement corrosion. Measurements were made on all specimens in two steps: before freezing and thawing cycles in 3% NaCl solution and after the cycles. The analysis of the obtained results allowed to determine differences in corrosion processes intensity on the reinforced bars in the concrete specimens depending on whether or not the air-entraining agent was added. Based on the analysis it was found that in the case of simultaneous action of chloride corrosion and frost it is advisable to use both blast-furnace slag cement and air-entraining agent. The use of only blast-furnace slag cement (although it is a chloride resistant cement), without the addition of air-entraining agent is insufficient.

Keywords: *reinforcement corrosion in concrete, influence of chlorides and frost, galvanostatic pulse method, blast-furnace slag cement, air-entraining agent*

INTRODUCTION

The durability of reinforced concrete structures is closely linked with the reinforcement protection [1,2,3,4]. The reinforcement protection can be ensured by the use of a suitable concrete coating, i.e. a coating of appropriate thickness and made of suitable components. Proper requirements for coatings are strictly described in the Eurocode 2 standard. Well designed and constructed concrete coating allows the building to be used for many years without failure and thorough repairs in accordance with the assumed construction class [1,2,4,5]. The type of cement has significant impact on the quality of the coating [6,7,8,9].

Depending on the environmental conditions in which the building is used, various cements types are recommended [9]. In the case of the risk of chloride corrosion (most often caused by the use of de-icing agents in winter on roads, bridges and viaducts or as a result of sea water on coastal facilities), blast-furnace cements such as CEM III are highly recommended [6,10]. The use of such cement makes the bonding and hardening processes of concrete slower and different from commonly used Portland cement. Concrete with blast-furnace cement is more compact and airtight, with no large capillary pores and no large shrinkage formation. The blast-furnace cement concrete effectively limits the penetration of various substances inward such as chloride ions thus avoiding the passive layer damage and corrosion of the reinforcement.

Unfortunately, often chloride corrosion is associated with frost and multiple freezing and thawing of the concrete components. In such cases, the use of blast-furnace cements CEM III (although they have higher resistance to chlorides) may be insufficient. However, it is known that the air-entraining agent addition improves the resistance of concrete to frost [11,12,13].

This paper presents the tests results to evaluate the effect of air-entraining agent addition on the corrosion intensity of the reinforcement in concrete specimens with CEM III/A cement which have been subjected to 120 cycles of freezing and thawing in 3% NaCl solution. The research to determine the reinforcement corrosion occurrence and to estimate the reinforcement corrosion activity was conducted by the non-destructive electrochemical method.

EXPERIMENTAL

Twelve reinforced concrete specimens 210×228×100 mm were prepared for the tests. The specimens were made of C30/37 concrete, consistency class S3, water/cement ratio w/c = 0.43. Concrete mix components per 1m^3: blast-furnace slag cement CEM III/A 42.5 N-LH/HSR/NA - 384 kg, sand - 680 kg, gravel 2/8 - 600 kg, gravel 8/16 - 650 kg, water 166 l, plasticizer Adva Flow 440 - 0.6% of cement volume and air-entraining agent Darex AEA W (LP) - 0.4% of cement volume (mass dosing were used after conversion). Specimens were made in two groups:

- group S-0 (6 samples) - specimens made without air-entraining agent addition,
- group S-A (6 samples) - specimens made with air-entraining agent addition.

Two parallel ϕ8 mm diameter ribbed bars of BST 500 steel were placed in each specimen at a spacing of 70 mm from the side edges of the specimen (Fig. 1). The reinforcement coating was 25 mm thick.

All specimens were made in an identical laboratory conditions. The specimens were removed from a moulds the next day after forming and were kept in a laboratory hall at temperature of 20°C ± 2°C and relative humidity of 50% ± 5%.

Electrochemical studies to determine the reinforcement corrosion occurrence and reinforcement corrosion activity were made by the use of the galvanostatic pulse method, described in details in [14,15,16,17]. The basis of this method is the assumption that the reinforcement corrosion in concrete is an electrochemical process. Therefore the measurements of some electrical parameters (which indicate the ongoing reinforcement corrosion) and then the comparison them to the benchmark database allows to indirectly assess the progress of the corrosion process. We can do so called basic measurements and then we measure the reinforcement stationary potential and concrete coating resistivity only. These measurements are not accurate. We can also do so called advanced measurements. In this case apart from the measurements of reinforcement stationary potential and concrete coating resistivity the corrosion current density is measured too. In the presented studies the advanced measurements were made. The research was conducted in two stages: phase I - recursive measurements made on all S-0 and S-A specimens (these are the reference measurements for subsequent measurements); phase II - measurements made on the same specimens which were subjected to 120 freezing and thawing cycles in a 3% NaCl solution to induce chloride corrosion. Specimens were placed in a frost resistance test chamber with an automatically controlled test program (temperature range: + 18°C ÷ -18°C) and completely submerged in solution.

In both phases, the measurements were made on all specimens according to the guidelines given in [14]. On the surface of each specimen 4 measurement points were placed evenly over the reinforcing bars (two points above each bar) where the following parameters were measured: corrosion current density, stationary reinforcement potential and concrete coating resistivity (Fig. 1).

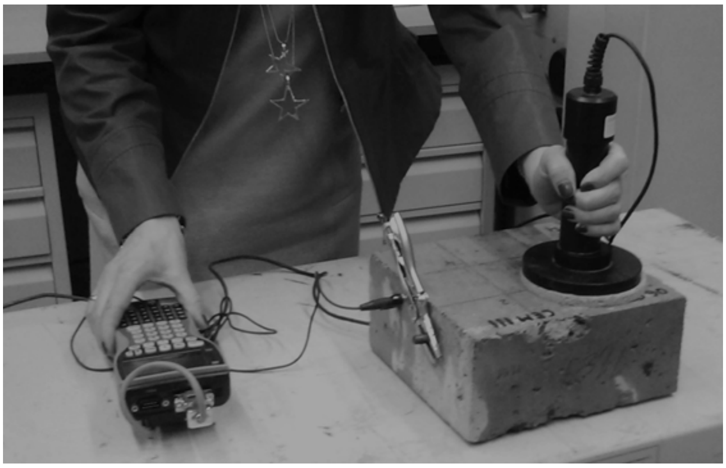

Fig. 1. Measurement on one of the tested specimens by the use of the galvanostatic pulse method

Table 1. *The criteria for assessing the reinforcement risk corrosion degree [14]*

<table>
<tr><th colspan="5">Criteria for assessing the degree of reinforcement corrosion risk</th></tr>
<tr><td rowspan="11">Advanced measurements</td><td rowspan="6">Basic measurements</td><td rowspan="3">Reinforcement stationary potential, E_{st} [mV]</td><td>> -200</td><td>5% of corrosion probability</td></tr>
<tr><td>-350 ÷ -200</td><td>50% of corrosion probability</td></tr>
<tr><td>< -350</td><td>95% of corrosion probability</td></tr>
<tr><td rowspan="3">Concrete coating resistivity, Θ [kΩ·cm]</td><td>≥ 20</td><td>small corrosion probability</td></tr>
<tr><td>10 ÷ 20</td><td>medium corrosion probability</td></tr>
<tr><td>≤ 10</td><td>high corrosion probability</td></tr>
<tr><td colspan="2" rowspan="5">Corrosion current density, i_{cor} [μA/cm^2]</td><td>< 0.5</td><td>not forecasted corrosion activity</td></tr>
<tr><td>0.5 ÷2.0</td><td>insignificant corrosion activity</td></tr>
<tr><td>2.0 ÷ 5.0</td><td>low corrosion activity</td></tr>
<tr><td>5.0 ÷ 15.0</td><td>moderate corrosion activity</td></tr>
<tr><td>> 15.0</td><td>high corrosion activity</td></tr>
</table>

The obtained results were compared to the benchmark results database [14], presented in Table 1. Taking into account the obtained values of the stationary reinforcement potential and the concrete coating resistivity the reinforcement corrosion probability in the examined area could be estimated, and based on the corrosion current density the reinforcement corrosion activity could be estimated.

DISCUSSION

Considering the obtained results based on the benchmark database (Table 1), the probability of corrosion in the studied area could be estimated and the reinforcement corrosion activity of the specimens was predicted. Initially the results from all measurement points on all specimens were analysed. Then, from each specimen one measurement point was selected, where the value of corrosion current density (the most reliable parameter) was the highest after the second stage of the test. This point in each specimen determined the degradation degree of the whole specimen. In the further part of the study the results obtained at these points were analysed and compared as representative of the whole specimen.

Corrosion current density

In phase I the corrosion current density measured on all specimens S-0 and S-A did not exceed $i_{cor} = 2$ μA/cm^2 (Fig. 2), which with respect to the given criterion (Table 1), indicated "insignificant reinforcement corrosion activity". On the basis of the corrosion current density results obtained in phase II (i.e. after 120 freezing and thawing cycles in 3% NaCl) it can be seen that in all specimens S-0 the corrosion current density increased considerably i_{cor} = 6.42÷9.73 μA/cm^2, which indicated "moderate reinforcement corrosion activity" (Fig. 2). In the specimens S-A, although they were subjected to the same freezing and thawing cycles and chlorides activity, the corrosion current density increased only slightly: in the four specimens did not exceed $i_{cor} = 2$ μA/cm^2 and in two specimens reached $i_{cor} = 3.86$ μA/cm^2 (Fig. 2) and nowhere has crossed the limit of "insignificant reinforcement corrosion activity".

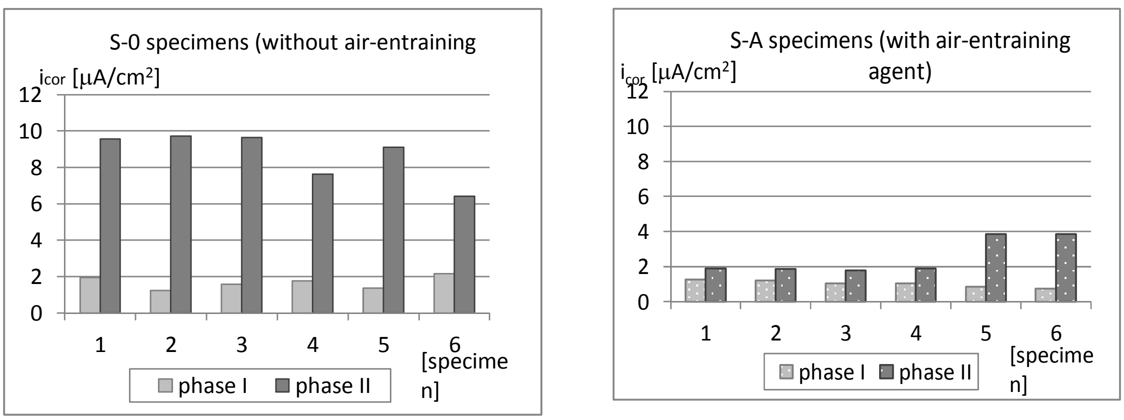

Fig. 2. Results of the corrosion current density measurements

Reinforcement stationary potential

The results of reinforcement stationary potential measurements were consistent with corrosion current density measurements. In phase I, the reinforcement stationary potential values measured on all specimens S-A and three specimens S-0 did not exceed E_{st} = -200 mV (Fig. 3), indicating "5% corrosion probability" (Table 1), and in the remaining three specimens S-0 slightly exceeded E_{st} = -200 mV (E_{st} = -220 ÷ -228 mV), indicating "50% corrosion probability".

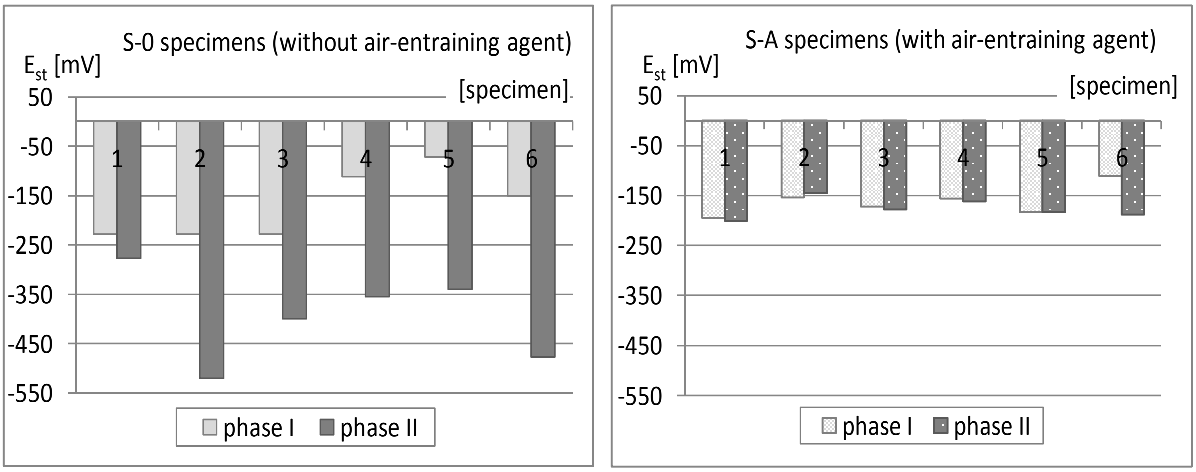

Fig. 3. Results of the reinforcement stationary potential measurements

In the second phase of the study in four specimens S-0 the values of stationary reinforcement potential exceeded E_{st} = -350 mV (extremely E_{st} = -521 mV), (Fig.3) indicating an increase in the corrosion probability to 95% (Table 1); in two specimens the values indicated the "50% corrosion probability" (E_{st} = -278 mV and E_{st} = -340 mV). In specimens S-A the values of the reinforcement stationary potential have hardly changed, in any specimen did not exceed E_{st} = -200 mV (Fig. 3), which still indicated "5% corrosion probability" (Tab. 1).

Concrete coating resistivity

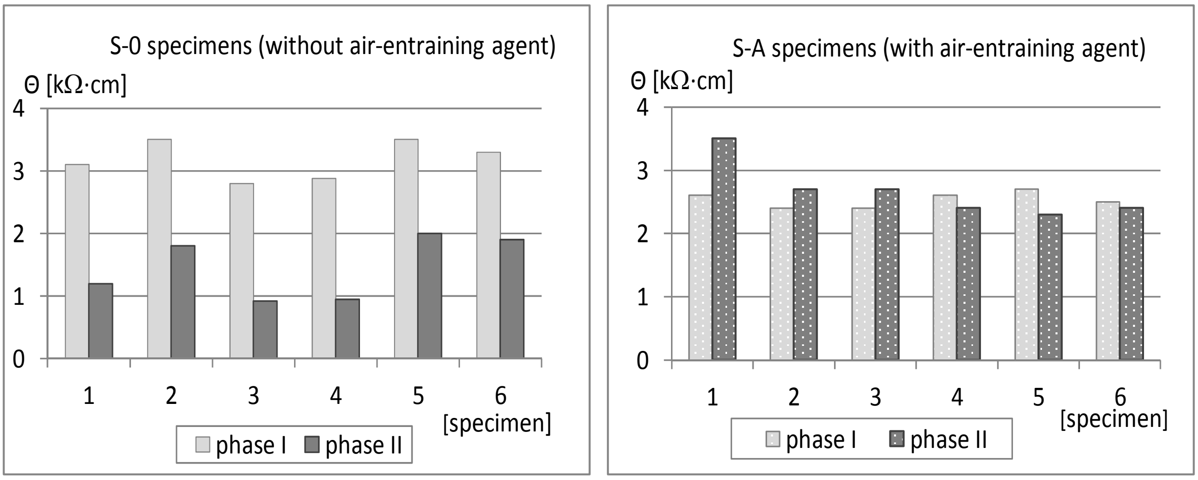

Fig. 4. Results of the concrete coating resistivity measurements

The results of the concrete coating resistivity measurements made on all specimens S-0 and S-A, in both phase I and phase II, indicated a high corrosion probability (Table 1), which was rather impossible. However, the application of the air-entraining agent had some influence on the obtained values. In the phase I of the tests in all specimens S-0 and S-A, the concrete coating resistivity was Θ = 2.4 ÷ 3.5 kΩ·cm (Fig. 4). In phase II of test in all specimens S-0 the values of the concrete coating resistivity dropped to Θ = 0.9 ÷ 2 kΩ·cm (Fig. 4), but in the specimens S-A the values almost did not change (in 3 specimens even increased); they were Θ = 2.3 ÷ 3.5 kΩ·cm (Fig. 4).

CONCLUSIONS

On the basis of the conducted tests of the reinforcement corrosion risk in the reinforced concrete specimens with blast-furnace cement CEM III/A, which were subjected simultaneously to 120 freezing and thawing cycles in 3% NaCl, it was found that:

1. To increase the resistivity of reinforced concrete to the simultaneous action of chloride corrosion and frost, it is necessary to use both blast-furnace slag cement and aeration into concrete. The use of only blast-furnace cement (although it is a cement with increased resistance to chlorides), without the addition of air-entraining agent, is insufficient.
2. Galvanostatic pulse method allow to estimate the corrosion degree risk of the reinforcement in concrete specimens in a non-destructive way but advanced testing is required. Performing the basic research only can lead to misleading conclusions.
3. Corrosion current density measurements (which are performed by conducting advanced research) are the most reliable and allow for assessment of the reinforcement corrosion activity. Based on them, it was found that in specimens S-0 (without air-entraining agent) the reinforcement corrosion activity after 120 freezing and thawing cycles in 3% NaCl increased on average by 7.07 $\mu A/cm^2$, whereas in specimens S-A only by 1.51 $\mu A/cm^2$.
4.The stationary reinforcement potential measurement was consistent with corrosion current density measurements but less precise.
5. Measurements of concrete coating resistivity proved to be unreliable. The concrete coating resistance values obtained from measurements on all specimens both in the first phase of the test and in the second did not exceed Θ = 10 kΩ·cm, suggesting a high probability of corrosion in the examined area. These results are not reliable. Such values were also obtained by the author during previous studies conducted on fresh specimens [17]. However, measurements made on real structures components used over a long period of time gave real results [17].

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