Impact of Environment Conditions on the Degradation Process of Selected Reinforced Concrete Elements

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Abstract. The environment negative impact on concrete can lead to deterioration its properties and the same to durability reduction of reinforced concrete structures. The main reasons of reinforced concrete elements destruction are carbonation of concrete, chemical corrosion, frost as well as mechanical defects that can damage the concrete cover and initiate the corrosion process on reinforcement. The intensity of destructive processes is closely linked with the intensity of environment factors action. Therefore, it can be assumed that the impact of CO₂, humidity changes and temperature will be much bigger in case of outdoor elements than the interior elements. The paper presents results of the experimental test that was carried out on two kinds of reinforced concrete poles: outdoor power pylons and columns of frame building structure in the public utility building. The examined elements were exploited on the same location in the same time – fifty years, but in different environment conditions. The semi-non-destructive electrochemical method was used to measure of reinforcement corrosion intensity in both kinds of poles. The results allowed to evaluate the corrosion activity of reinforced rods and to predict the corrosion progress in time. At the same time, the samples of cover concrete were taken from the poles to carry out the phase composition by X-ray diffraction and thermal analysis. The results allowed assessing the effect of environment conditions on the degree of destruction two kinds of reinforced concrete poles. The electrochemical test showed differences of the reinforcement corrosion activity as well as the research of concrete samples; however, the differences were not as significant as should be supposed.

1. Introduction

The conditions of the external environment in which the building is used have a significant impact on its durability [1-3]. Especially dangerous for the reinforced concrete elements are: aggressive action of carbon dioxide from the air, chloride and sulphate salts, as well as variable values of temperature and relative humidity. As a result of the factors mentioned above, the physical and chemical processes start and develop on the concrete surface, which leads to the loss of the cover layer protective capacity over the reinforcing bars as well as to the corrosion of steel [2-5]. The concrete carbonation process is widely known i.e. the reaction of carbon dioxide from the air with calcium hydroxide from hardened cement paste [6, 7]. In the initial phase of this process, the surface layer of the concrete seals (which is a positive phenomenon) but after a long time the process duration leads to structural changes in the concrete and the number of large pores increases, which negatively affects the protective role of concrete over the reinforcement. As a result of the slow process of concrete carbonation the initial high pH (pH=12.6) falls, which can result in the destruction of the passive layer on the reinforcement
(at pH <11.8) and initiate steel corrosion [2, 5, 7, 8]. It should be added that this phenomenon is so
dangerous that the resulting changes in the concrete cover can be hardly visible or even invisible, yet
corrosion of the reinforcement can be significant and lead to the disintegration of concrete from the
inside. A separate issue is the mechanical damage to the concrete cover. As a result, the concrete
cracks and cavities often occur which although indicate degradation of the element and facilitate the
penetration of aggressive factors into the concrete structure do not always prove the advanced
corrosion process of reinforcing steel. In both cases as a result of the carbonation process and as a
result of mechanical damage to the reinforced concrete elements of the structure the time has a
significant influence on the progressive corrosion of concrete and steel [5, 8].

The aim of the conducted research was to compare the effects of environmental conditions
influence on the damage degree to reinforced concrete poles operated in a similar period of ~ 50 years
and verification of test results compliance performed by different methods. The tests were performed
on two types of poles: pylons exposed to direct atmospheric conditions (type P) and internal columns
of the residential building structure used in favourable conditions (type C). The tests included:
performing electrochemical measurements using the galvanostatic impulse method to assess the
degree of reinforcement corrosion and determine the areas with a defined corrosion probability;
performing material tests of the mineral composition of concrete covering with X-ray method and the
amount of carbonates formed by thermal analysis, as well as estimating the compressive strength of
concrete using the sclerometric method.

2. Elements and test methods
The research involved three double-pylons (type P) shown in figure 1a. Selected pylons were exposed
to a long-lasting influence of natural environment conditions including primarily the negative effect of
atmospheric factors. The age of pylons was estimated at 50 years. The P-type pylons were reinforced
with ribbed bars with a diameter of 8 mm, the thickness of the concrete cover was on average 8 - 10
mm.

![Figure 1. The selected tested poles: a) P-type pylon; b) C-type column](image)

The second type of poles were four reinforced concrete columns that are internal elements of the
building structure (type C) (figure 1 b). The age of these columns was estimated at 48 years. The C-
type columns were reinforced with ribbed bars with a diameter of 20 mm, the thickness of the cover
was 20 - 25 mm, additionally the columns were covered with ~ 10 - 15 mm with a cement-lime plaster
layer.

Electrochemical tests carried out using the galvanostatic impulse method, consisted in the
measurements of stationary reinforcement potential, concrete cover resistivity and corrosion current
density - parameters that indirectly allow assessing the probability of the reinforcement corrosion in
the tested area and estimating the corrosion activity of the tested rods. The measurements were made with the GalvaPulse - 5000™ device on each of the poles at three measuring points located directly above the main reinforcement and spaced every 30 cm. The pylons measurements were performed in the summer at the temperature of around T = 27°C and humidity of RH = 46%. The measurements of C-type columns were made in the building in the autumn period, with the interior temperature of about 3°C and the humidity of RH = 76% (the building was during the renovation - no heating). The obtained results were analysed based on the criteria for assessing the degree of reinforcement corrosion risk (table 1) [9].

### Table 1. Criteria for assessing the degree of reinforcement corrosion risk [9]

| Criteria for assessing the degree of reinforcement corrosion risk | Condition | Probability |
|---------------------------------------------------------------|-----------|-------------|
| 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_{corr} [μA/cm²]                 | < 0.5     | not forecasted corrosion activity |
|                                                             | 0.5 - 2.0 | irrelevant corrosion activity |
|                                                             | 2.0 - 5.0 | low corrosion activity |
|                                                             | 5.0 - 15.0 | moderate corrosion activity |
|                                                             | > 15.0    | high corrosion activity |

Material tests of concrete cover included evaluation of the phase concrete composition taken from both types of poles using X-ray analysis and thermal methods (DTA-TG) [10]. Thermogravimetric analysis allowed determining the content of calcium carbonate and calcium hydroxide in the poles concrete cover. On each pole, accompanying tests were also carried out - concrete compressive strength measurements using a sclerometric method.

### 3. Results and test analysis

The average strength of P-type pylons concrete obtained by the sclerometric method amounted to ~37 MPa. However, the average strength of C-type columns concrete was ~ 55 MPa.

The electrochemical test results [8] as regards reinforcement stationary potential measurements as well as concrete cover resistivity and corrosion current density that were performed on two kinds of poles are presented in the table 2.
Table 2. The electrochemical test results performed on two kinds of poles

| Nº  | Corrosion current density, $i_{\text{cor}}$ [μA/cm²] | Reinforcement stationary potential, $E_{\text{st}}$ [mV] | Concrete cover resistivity, $\Theta$ [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 level [9]

The obtained results were analysed based on criteria for assessing the degree of reinforcement corrosion risk (table 1) [9]. The values of corrosion current density that were measured on P-type pylons indicated on: "high corrosion activity" of reinforcement in the P1b pylon (maximum $i_{\text{cor}} = 21.76$ μA/cm²), "moderate corrosion activity" of reinforcement in P1a pylon (maximum $i_{\text{cor}} = 5.7$ μA/cm²), and in all other pylons the reinforcement corrosion current activity was "irrelevant" (less than $i_{\text{cor}} = 2.0$ μA/cm²). The values of this parameter were clearly lower in the C-type columns (C1-C4). The value of reinforcement corrosion current density was not larger than $i_{\text{cor}}=0.5$ μA/cm² in any tested place. These results indicated the "not forecasted corrosion activity" of reinforcement. Based on the second parameter – the reinforcement stationary potential, it can conclude that the reinforcement corrosion probability was very low (5%) in both kinds of poles. The value ranges results were similar and were as follows: for P-type pylons: $E_{\text{st}} = -86 - 29$ mV, and for C-type columns: $E_{\text{st}} = -144 - 1.87$ mV. It has to be added that these values were inconsistent with the visible differences between the reinforcement corrosion in two kinds of poles. The reinforced bars in the C-type columns were pure while the bars in P-type pylons were really corroded. The third measured parameter – concrete cover resistivity, allowed for more precise determining the reinforcement corrosion probability in two kids of poles. The results of measurements that were performed on the P-type pylons indicated on "medium" corrosion probability" in four points, and in all other points the probability of reinforcement corrosion was "high". The concrete cover resistivity measured on C-type columns was higher than $\Theta = 20$ kΩ·cm in twelve points indicating "small corrosion probability", and only in two points this value was less than $\Theta = 10$ kΩ·cm indicating "high corrosion probability". In one point the value was $\Theta = 15.6$ kΩ·cm, so the corrosion probability was "medium".

The results of the concrete phase composition taken from the surface layer of the tested elements are shown in figure 2. In the phase composition of concrete cover from P-type pylons, the presence of the metastable form of calcium carbonate-vaterite and calcite was observed, which arose as a result of carbonation processes. It was also found that there are typical phases that are cement hydration products, i.e. ettringite, portlandite and reflections from aggregate, i.e. quartz, albite. It is not possible to indicate clearly whether ettringite reflections in this case prove the sulphate corrosion of concrete. Small amounts of this phase can be found in concrete for a number of years [11]. It should be noted, however, that the source of sulphate ions may come from vehicles exhaust gases as well as heat and power plants or industrial plants, which the tested materials were exposed to and lead to sulphate corrosion [12].
The above analysis clearly indicates the loss of protective properties of concrete cover and thus increase the probability of reinforcement corrosion. The presence of cement hydration products, i.e. portlandite and concrete carbonation products, i.e. vaterite and calcite was also recorded in the concrete taken from the supporting structure C-type columns. There were no reflections from ettringite.

Figure 3 presents the results of thermogravimetric tests carried out on concrete specimens taken from fragments of the P-type pylons cover (figure 3a) and C-type columns (figure 3b).
The analysis of thermograms in the temperature range of calcium carbonate decomposition indicated significant losses in mass in both tested specimens, respectively: 7.67% (P-type pylons) and 5.76% (C-type columns). The analysed loss in mass in the temperature range of 500-750 °C is related to the decomposition of two forms of calcium carbonate: a less stable vaterite phase (which decomposes at a lower temperature) and better developed calcite (which decomposes at higher temperatures). According to the studies described in [13], vaterite is a carbonation product mainly of the C-S-H phase. The vaterite then goes into calcite. Due to the overlap of vaterite and calcite...
decomposition peaks, their content cannot be clearly defined [10]. The above analysis indicates the ongoing carbonation process clearly higher in P-type pylons specimens. At the same time, it should be noted that the relatively high content of calcium carbonate in concrete specimens from C-type columns could be associated with the presence of cement-lime plaster, which has not been thoroughly removed from the surface of the columns.

4. Conclusions

- Electrochemical tests - measurement of the corrosion current density and concrete cover resistance indicate a much greater degree of the reinforcement corrosion in free standing power pylons than in the internal columns of the building structure (in which corrosion was not found).
- In the samples taken from concrete covers of pylons and columns, concrete corrosion due to carbonation was found, as indicated by the presence of calcium carbonate phases: vaterite and calcite. However, the process advancement is visible higher in pylons.
- The research confirmed that the process of concrete carbonation in pylons exposed to the negative impact of environmental conditions (changing weather conditions) is much more intense than in the columns constituting internal parts of the structure.
- The comparison of the test results of pylons, which were exploited for ~ 50 years in extremely different environmental conditions allowed to verify the validity of the methods used to assess the degree of concrete degradation and reinforcement of the tested elements.
- Differences in the results of electrochemical tests carried out on two types of pylons indicate that the galvanostatic impulse method allows assessing the degree of reinforcement corrosion probability but the measured parameters to a different extent reflect the state of reinforcement. The most reliable are the measurements of the corrosion current density and the least the reinforcement stationary potential.
- Examination of concrete samples taken from fragments of pylons covers is an important complement to electrochemical tests; comprehensive research allows for their mutual verification.

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