Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

LONG-TERM CORROSION BEHAVIOR OF CONCRETE STRUCTURES IN CHLORIDE-BASED INDUSTRIAL ENVIRONMENTS: CASE STUDIES

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The paper presents two cases of reinforced and prestressed concrete structures damaged by corrosion in chloride-based industrial environments having as main aggressive agents: chlorine, hydrochloric acid and chlorides. To evaluate the corrosion damage of the concrete structures, *in-situ* and laboratory tests using specific investigation techniques were performed. Investigation of the damage state of structures revealed that many of the examined structural elements showed severe damage due to corrosion. This damage was in various stages of development and had a different influence on the resistance, stability and durability of structures. The corrosion-damage of the structural elements was favoured and accentuated by the absence of efficient intervention measures (repair, corrosion protection) for these elements. In order to ensure normal service conditions of the reinforced and prestressed concrete structures there were proposed intervention measures to remedy existing damages, regarding repair, strengthening, replacing, and corrosion protection of the damaged elements.

Keywords: Elements, Aggressive agents, Durability, Investigation, Damage, Intervention measures.

1 INTRODUCTION

The durability of the reinforced and prestressed concrete elements in aggressive environments is a topic of major importance for the service life of civil and industrial structures. The corrosion of the steel in concrete is one of the most frequent pathologies, which affect the service capacity of the concrete structures by reducing the mechanical capacity and by cracking the concrete.

During the last decades, many cases of unsatisfactory durability of concrete structures located in aggressive environments are asserted, i.e., damage of their structural elements after various service periods.

The experience acquired after performing a large number of technical surveys and researches on the state of the reinforced and prestressed concrete structures/elements of various industrial plants, engineering works or public buildings, has shown that the most important corrosion damage cases which could affect the resistance, stability and durability of structures occur in chemical industry or other industries that involve technological chemical processes (Pepenar 1994).

Compared to other aggressive environments, the environments containing chloride-based aggressive agents are among the most aggressive and complex industrial environments. They present a specific and complex aggressiveness upon concrete structures, affecting at the same time both the concrete and as well as its steel reinforcement (Pepenar 1979, C 012/1 2007). The basic action of these aggressive environments is obvious in industrial zones including factories specialized in chemistry, petro-chemistry, metal plating, pulp and paper, metallurgy, etc.

The paper presents two cases of reinforced and prestressed concrete elements damaged by corrosion in chloride-based industrial environments.

2 CORROSION DAMAGES: CASE STUDIES

To evaluate the corrosion damage state of the concrete structures, *in-situ* and laboratory tests using specific investigation techniques (Pepenar 1999) were performed.

The investigation of the damage state of the concrete structures showed that some of the examined elements presented damage due to corrosion, occurring to various extents. This damage was in various stages of development and had a different influence on the resistance, stability and durability of the structures.

Two cases are further presented in order to exemplify the corrosion damages of the reinforced and prestressed concrete elements, subjected to corrosion caused by chloride-based industrial aggressive environments.

2.1 Case 1: Reinforced Concrete Elements

The first case refers to the corrosion damage of the reinforced concrete elements in a sodium chloride electrolysis industrial building.

The industrial building of fabrication has the bearing structure composed of reinforced concrete frames (columns and beams), an intermediate technological reinforced concrete floor and reinforced concrete roof elements and masonry walls. Within this structure the fabrication process of raw material (sodium/potassium chlorides) and of finite products (sodium/potassium hydroxides and chlorine gaseous) occurs. The structural elements were subjected to the long term action of a strongly aggressive environment, consisting mainly of chlorine and hydrogen chloride vapours and gases, hydrogen chloride solutions, chlorides and hydroxides.

The investigation of the damage state of the reinforced concrete elements, after 22 service years, showed that the majority of the examined roof elements (caissons and beams) presented severe damage due to corrosion, occurring to various extents and in different stages of development. The results of the on-site investigation are concisely presented as follows:

- Concrete cracking along the longitudinal reinforcements, followed by spalling of the concrete cover and by uncovering of the steel reinforcements, remaining in contact with aggressive atmospheric agents (see Figure 1);
- Advanced corrosion of the longitudinal and transversal (stirrups) steel reinforcements, having the effect of reducing their cross-section and in the case of transversal reinforcement (stirrups), resulting even in the complete destruction, in some areas, due to corrosion by chloride ions (see Figure 2).

Figure 1. Reinforced concrete roof elements: cracking and spalling of concrete cover; uncovering of the steel reinforcements.

Figure 2. Reinforced concrete beam: advanced corrosion of the steel reinforcements, reduction of the diameter and fracture of the stirrups, in some areas, due to the corrosion by chloride ions.

The results of the laboratory tests performed on a large number of concrete samples extracted from the corrosion affected construction elements, showed the following:

- The pH of the aqueous suspension of the samples varied between 5.5 and 8.5, values which indicate a total removal of the alkalinity of the concrete cover subjected to the aggressive agents with acid character, i.e., the loss of the concrete capacity to ensure the protection of the steel due to the passivation phenomenon, fact which confirms the results of the tests performed *in-situ*;
- The water soluble chloride ions concentration in the concrete samples ranged between 1.42% and 3.19% Cl^- (by weight of concrete), values to which Cl^- presents a strong aggressive effect on the steel reinforcements.

2.2 Case 2: Prestressed Concrete Elements

A second case refers to the corrosion damage of the precast prestressed concrete roof elements in an industrial building. Within this structure the technological process of metal plating occurs.

The industrial building has the bearing structure composed of reinforced concrete frames (columns and beams), prestressed concrete roof curved caissons, masonry walls and technological reinforced concrete basement. The structural elements were subjected to the long term action of a strongly aggressive environment, consisting mainly in hydrogen chloride vapours (2.8…32.0 mg/m^3 air), with high air humidity.

The investigation of the damage state of the ECP 18 x 1.5 m roof curved caissons, after 14 service years, showed the existence of severe damage due to corrosion, mainly in the ribbed elements, occurring to various extents and in different stages of development. The results of the *in-situ* investigation are concisely presented as follows:

- Concrete cracking along the longitudinal reinforcements;
- Advanced corrosion of the non-pre-tensioned steel reinforcement (ø 20 mm steel bar), at the end of the elements and at the bottom of the ribs, which caused - by increasing the volume of corrosion products (5…10 mm rust layers) - severe concrete cracking, along the longitudinal reinforcements, on 2…3 m from the supports, followed by spalling of the concrete cover and by uncovering of the steel reinforcements (See Figure 3);

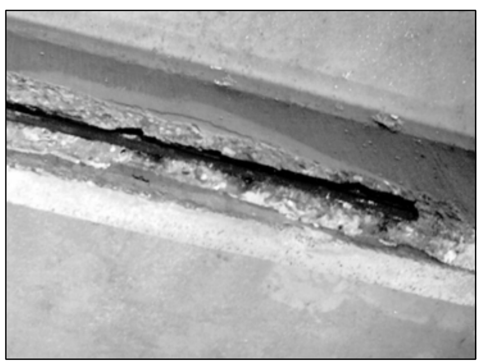

Figure 3. Prestressed concrete roof element ECP: cracking and spalling of the concrete cover; advanced corrosion of the non-pre-tensioned steel bar at the bottom of the rib.

- Severe corrosion of the pre-tensioned bottom steel strands TBP 12 (7ø 4 mm), with a considerable reduction of the cross-section and diffusion of the steel corrosion products in the concrete within a radius of 10…20 mm around the prestressing steel strand (See Figure 4).

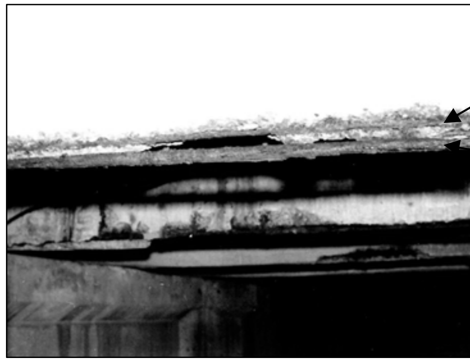

Figure 4. Prestressed concrete roof elements ECP: cracking and spalling of the concrete cover; advanced corrosion of the non-pre-tensioned bar and pre-tensioned strand.

The corrosion of the non-pre-tensioned and pre-tensioned steel reinforcements, specific to the action of chloride-based aggressive environments, was favoured by the inadequate thickness of the concrete cover layer, compared to the aggressivity of the existing environment inside the industrial building, as well as by the absence of an efficient corrosion protection of the prestressed concrete roof elements.

The damage of the ribs in the end zones, caused by the corrosion of the steel reinforcements, with concrete spalling on the height of ribs, resulted, on one hand, in a considerable reduction of the actual cross-section of the elements, and on the other hand, in a reduction of the thickness of the concrete cover layer on the upper pre-tensioned strands, at the ribs' bottom and on the sides. The severe corrosion damage of the ribs, which affects the bearing capacity of the elements, is obvious for half of the existing elements, but incipient damage may also be noticed in other elements.

The results of the laboratory tests performed on concrete samples extracted from the corrosion affected construction elements, showed the following:

- The pH of the aqueous suspension of the samples varied between 5.5 and 11.0, values which indicate a total or partial removal of the alkalinity of the concrete cover subjected to the aggressive agents with acid character, i.e., the loss of the concrete capacity to ensure protection of the steel due to the passivation phenomenon, fact which confirms the results of the tests performed *in-situ*;
- The water soluble chloride ions concentration in the concrete samples ranged between 0.42% and 0.70% Cl^- (by weight of concrete), values to which Cl^- presents a strong aggressive effect on the steel reinforcement.

Taking under consideration the advanced corrosion damage state of some reinforced and prestressed concrete elements and the accelerated evolution of the corrosion processes once initiated, which affect the resistance, the stability and the durability of the investigated elements/structures, intervention measures were proposed, regarding the repairing, strengthening or replacement of the damaged elements (Pepenar 1994). The intervention measures consisted of:

- The replacement of the prestressed concrete roof elements with galvanized steel elements and ensuring a good corrosion protection for these new elements by using protective paint systems, in accordance with the specific technical regulations (GP 121/1 2013);
- The repairing of the local damage of the reinforced concrete elements by special cement mortars and the use of corrosion protection by employing protective paint systems, in accordance with the specific technical regulations (C 170 1987).

Along with the intervention measures aimed at the replacement/repair of the elements damaged by corrosion, actions aiming maintenance measures as a result of the monitoring of the service behavior of elements/structure are proposed.

3 CONCLUSIONS

The results of the research on the service behavior of the reinforced and prestressed concrete elements of two industrial buildings, after 14…22 years of service in chloride-based industrial environment, revealed the existence of advanced corrosion-induced damage of the concrete roof elements, which could affect the resistance, stability and durability of the structures.

The corrosion damage of the reinforced and prestressed concrete elements in this aggressive environment occurs, mainly, as a consequence of the specific corrosive action of the chloride ions on the steel reinforcements embedded in concrete.

Damage due to corrosion was caused by the severe service conditions of the elements/structures and was favoured by the absence of efficient maintenance measures (repair, corrosion protection) of these elements.

In order to ensure normal service conditions for the reinforced and prestressed concrete elements, intervention measures to remedy existing damages and systematic monitoring of the service behavior of the reinforced and prestressed concrete elements/structures was required.

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