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Corrosion degradation and repair of a concrete bridge

A. Guettala · A. Abibsi

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Abstract Reinforced concrete corrosion has been widely reported in the literature over the last two to three decades even though certain cement concrete works remain in excellent state after more than one century of exposure to severe climatic conditions. This type of damage is responsible for the huge financial costs spent each year on the repair of deteriorated structures all over the world. This article describes the diagnosis carried out on the degradation of a reinforced concrete bridge put into service only 20 years back as well as the follow up repair. The stages of repair and reinforcement are discussed as well as its state after repair. The processes leading to damage and necessary repair strategies and procedures to avoid further damage under the given environmental conditions were obviously not understood by the designers of the repair works. It's also shown in this study the importance of maintenance and regular inspection of a given cement concrete work or the lack of it as is the case.

Keywords: Diagnosis, Degradation, Design, Corrosion, Repair

Résumé *La corrosion du béton armé a été largement reportée dans la littérature pour les deux dernières décennies malgré que certaines structures en béton armé demeurent dans un état excellent après plus d'un siècle d'exposition aux conditions climatiques sévères. Ce type d'endommagement est responsable des coûts financiers énormes dépensées chaque année dans la réparation des structures détériorées à travers le monde. Cet article décrit le diagnostique fait sur la dégradation d'un pont en béton armé mis en service il y' a seulement 20 années ainsi que le suivi après réparation. Les causes principales de la dégradation ainsi que les différentes étapes de réparation et le renforcement sont décrites et discutées. Des processus causant des endommagements et des stratégies nécessaires de réparation pour éviter encore plus de détérioration sous des conditions environnementales données n'étaient pas bien cernées par les concepteurs de ces travaux de réparation. Cette étude a montré aussi l'importance de la maintenance et de l'inspection régulière ou plutôt leur absence comme c'est le cas.*

Mots clés: Diagnostic, Dégradation, Conception, Corrosion, Réparation

A. Guettala · A. Abibsi
Faculty of Engineering Biskra University – Algeria

1. Introduction

Reinforced concrete has proved to be a reliable structural material with very good durability performance when properly used. However, the corrosion of the reinforcement is the main cause of the structural concrete deterioration [1, 2]. The exposure of these materials to a severe environment such as: temperature, deicing agents, humidity [3–6], aggressive ions mainly chlorides [7–9] and sulphates [10–13] makes them more vulnerable. Their durability depends also on the work design, material selection and their processing [14].

Concrete is a permeable material, where aggressive agents diffuse to reinforcing steel causing its depassivation and corrosion, when moisture and oxygen are available. Concrete is also brittle and always contains microcracks. When these microcracks combine in a network with macrocracks, the prevailing transport mechanism is not diffusion; it is rather the permeation of water and aggressive agents via water through the cracks to the reinforcement [15]. However, it is well established that the moisture and oxygen content in the concrete are the main parameter controlling the rate of corrosion [16]. Thus, when the concrete is dry, the corrosion shows negligible values (below 0.1 μA/cm^2). These values increase when the humidity goes up to values around 100 μA/cm^2 (in sea water) [17].

Concrete reinforcement corrosion has been widely reported in the literature over the last two to three decades. This type of damage is responsible for the huge financial costs spent each year on the repair of deteriorated structures worldwide.

Many are the approaches that can be used to mitigate corrosion of reinforcing steel, among which, protective coatings and sealers, galvanized steel, cathodic protection, concrete realkalinization and corrosion inhibitors are commonly employed [18, 19].

However, despite the very wide existing range of prevention means, with ageing and at some time in a given structure life, maintenance and repair is becoming an increasingly important part of the design and construction industry. Complex decisions have to be made in the selection of repair materials and systems in infrastructure rehabilitation. Compatibility of the repair material with the existing substrate is an important consideration if the repair is to withstand all the stresses induced by the influences, such as volume changes and chemical/electrochemical effects. Several types of concrete repair materials [8, 11, 20, 21] have been introduced and used through years. These have ranged from polymer modifiers for Portland cement based products to pure polymers such as epoxy resins and polysters based systems. Faced with the confusing array of new enhanced repair materials and systems being promoted by suppliers as well as the deficiencies in knowledge of corrosion and corrosion protection in concrete repair, methods of testing, and in the science of repair durability, the designer may be tempted to adopt a simplistic approach to the repair, which simply requires the use of a material with properties close to the existing concrete.

In any investigation or any repair, it appears necessary to proceed first in collecting the maximum of information: age, architectural plans, nature of the materials used (cement type, proportioning. . . etc) and the nature of the environment. A detailed visual inspection makes it possible to recognize the nature of the problem, to describe their localization and, if necessary, to follow their evolution.

The disorders appear in the shape of cracking, delamination and/or spalling of concrete. But the corrosion starts generally in the zones nearby without causing visible disorders yet. After having identified the origins of corrosion (chlorides, carbonation, sulphates, and/or others), and evaluated its extent (penetration depth), the use of non-destructive tests (measurements of wrapping and potential) makes it possible to determine the extent of the corroded zones correctly and to predict its evolution [22, 23].

The principal parameters governing the behavior of a given concrete structure with respect to corrosion are, in the order of their importance: the wrapping, the quality of the concrete and the environment [24, 25].

This article describes the diagnosis carried out on the degradation of a reinforced concrete bridge put into service 15 years ago. The principal causes of the acceleration of its degradation are highlighted. The stages of repair and reinforcement are discussed. The state of the work after 4 years of repair is also reported as well as the importance of regular inspection and maintenance; or the lack of these as shown in this study.

2. Bridge and disorders description

The work investigated here is located on the Route Nationale3, (RN3), 25 km from Biskra, (South-east of Algeria), Fig. 1.

It is about a horizontal mixed bridge of an overall length of 340 m, made up of 11 isostatic spans of 30 m each. The 10 m wide deck is composed of three metallic girders of 1.50 m height. These girders are linked by two butt-spacers, three intermediate-spacers and surmounted by a reinforced concrete slab. Its profile consists of an 8 m width roadway framed by two pavements of 1 m width. The roadway support is made of two reinforced concrete supports with wing walls

Fig. 1 General view of the bridge.

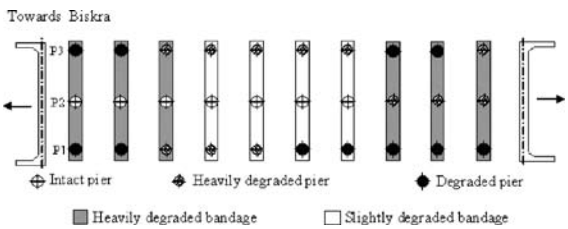

Fig. 2 Sight plan of the bridge.

and ten intermediate piles consisting of: 1.20 m width and 0.8 m height bandage resting on three circular piers of 1.0 m diameter, Fig. 2. The pile foundations established in the river soil are protected by metal sheeting embankment.

The concrete was proportioned with 400 kg/m^3 Portland cement - CPA 325 - with water/cement (W/C) ratio of 0.55; 750 kg/m^3 of round sand and 1100 kg/m^3 gravel coming from a quarry nearby.

2.1. Description of the disorders observed on the piles before repair

Many disorders were noticed on this work mainly cracking of the concrete and corrosion of the reinforcements causing the spalling of concrete. These degradations were observed on the beams of girders and on the piers, particularly, those protected by coffer dams in metal sheeting.

2.1.1. Pier caps

The bandages are mostly affected, some of which badly, Fig. 3. The degradations are of the following forms:

- advanced corrosion of the reinforcement;
- concrete spalling;
- multi-directional cracking of the concrete.

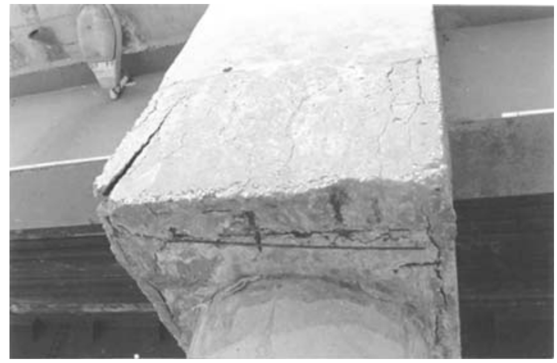

Fig. 3 Degradation of the cross beams.

It is at the girder ends that degradations are significant. In their median part, they are only slightly degraded. This can be explained simply by the stagnation of water at ends.

However, the bandages of the piles P6 and P7 are practically intact. The remainder of the bandages exhibit minor degradation.

2.1.2. Piers

We noticed that the intermediate piers are not affected; on the other hand certain bank piers (upstream and downstream) showed degradations. P1-p1, P2-p1, P2-p3, P3-p1, P3-p3, P4-p1, P5-p1, P9-p1, P9-p3, P10-p1 and P10-p3 are the most affected (Fig. 2). The following forms of degradation are noted:

- Parallel, vertical and equidistant cracks, the position of the cracks generally coincides with the position of reinforcing steel bars;
- Spalling at places and delamination of concrete plates;
- Significant corrosion of the reinforcements after removal of concrete.

2.1.3. Deck

The deck presents an overall satisfactory state.

3. Degradation causes

The construction of the bridge was carried out between 1983 and 1985 by the National Company of the Bridges and Work of Art (SAPTA). In 1994, hidden walls in full breeze blocks were built above the diagrids of the piles and the abutments as an urgent measure for countering possible acts of sabotage and terrorism. At least a dozen of bridges have been blown up all over the country in that period.

It was observed that the joints of roadways at the pavement level were not tight and this allowed rainwater to penetrate through the joints and pouring on the bandages where they are retained by the hidden walls before running out on the piers. The badly designed metal sheeting embankments form a basin like, retaining thus water.

The degradation was very significant in places of water flow indicating that the rain water is unusually very aggressive. The rain water analysis indicated that it is unusually very salty. After investigation, it appeared that the rain water salt content resulted from salts falling off the trucks making the shuttle between the salt layer, about 40 miles from Biskra. The rain helps the leaching of the deck and dissolves the salt. The resulted salty water penetrates through the loose inter-spans joints. Therefore, the principal cause of degradations is the chemical attack by the chloride ions causing the corrosion of the reinforcement and consequently the bursting of the concrete. The concentrated degradation at the level of the ends of the bandages is probably related to the bandages roof shape (symmetrical cross fall of 2.5%). The lack of cover (wrapping) in certain places; the bad quality of the concrete used indicated by the state of the facade and the presence of the gravel niches contributed enormously to corrosion of steels.

3.1. Corrosion mechanism

The protection of the reinforcements is related to two processes:

- Chemical process: the alkalinity produced during the cement hydration;
- Physical process: by wrapping, acting like a barrier with respect to the environment.
- It is accepted that the mechanism of the corrosion of the reinforcements proceeds in two successive stages:
- Starting phase: this corresponds to the penetration of the aggressive agents (mainly carbon dioxide, air and chlorides) through the layer of wrapping, until the starting of the corrosion of the reinforcement; destruction of "a passive film". This period depends mainly on the processes assuring corrosion elements to the reinforcement. It depends also on the chemical reactions taking place within the concrete. Undoubtedly, the cover quality (permeability, thickness...) have a fundamental role on the aggressive agents penetration [6, 7, 26].
- Growth phase: this corresponds to the formation of expansive iron oxides and to the damaging of the complex reinforcement-concrete. This period is particularly related to the rate of corrosion [13, 14, 26]. In our case, the corrosion observed is in its growth phase state. It is of uniform type (generalized) which occurs when the reinforcement is not protected any more and micro-cells corrosion can be formed over the whole surface.

4. Repair

Elimination of the immediate causes (to be done as an urgent work)

- Demolition of the hidden walls built on the diagrids of the supports;
- Installation of tight roadway joints including in the zones of the pavements;
- Widening of the openings of the gutter-spouts;
- Cutting the metal sheeting embankments which form a retaining water basin, avoiding therefore the water stagnation.

4.1. Piers

Repair relates to the damaged piers cited previously. The operations to be carried out are:

4.1.1. Surface preparation

- Remove all the loose and spalled concrete along the whole wall height (including the buried parts) until reaching the steel.
- Expose the reinforcements at least 2 cm beyond the cover.
- Remove all the corrosion products from the reinforcement bars by sand blasting. This operation must be done perfectly well.
- Rinsing and blast cleaning of all the concrete surfaces;
- The non-exposed bars to be sand blasted and cleaned with metallic brushes
- Treat the corroded reinforcement using an anti-corrosion product generally in the form of

Fig. 4 Repair of pier.

pre-proportioned kit composed of a resin and a hardener [27].

- Strengthen the affected reinforcement by adding new bars and making sure of the total covering at pier base; if the existing bars are corroded.

4.1.2. Framing

The framing, preferably, metallic, must be provided with spacers intended to ensure the wrapping of the reinforcements with an increase in the diameter of the piers by 20 cm compared to the initial diameter. This increase in the section will facilitate the casting of the concrete and also reinforce the pier resistance, Fig. 4.

4.1.3. Sheaths filling

The filling of the sheaths was done by a latex concrete. The latex concrete is not completely tight to the chloride penetration, but it offers a protection quite higher than that obtained with current concretes of Type B 30. According to various authors, the lifespan of the latex concrete patching (repair) should be at least fifteen to twenty years [28]. The formulation of the latex concretes is identical to that of the cement to take into account the water proportion contained in the latex emulsion and the significant effect of latex plasticization. According to the proportioning and the type of latex employed, the ratio W/C will be between 0.30 and 0.40. Due to the latexes diversity available, one should check the compatibility of the selected product with the cement using tests. The quantity of latex to be used (expressed in dry extract) ranges generally between 10 and 20% of the cement mass. In this repair work, 15% has been used.

Table 1 Typical formulation for 1 m^3 of latex modified concrete [28]

Cement, kg	Latex*, %	Gravel, kg	W/C	Sand, kg
390	15	985	0.3	805

*The amount of the latex used is relative to the cement quantity.

Polymer modified concrete has higher strength, lower water permeability, better resistance to chemicals, and greater freeze-thaw stability than conventional concrete [29]. The improvement of the properties is proportional to the added quantity of latex. With low proportioning, the gain is marginal; there is less of polymer to form film and the reduction of W/C ratio is less significant. However, an excessive proportioning is not economically justified. This causes an exaggerated air drive and in all cases, the improvement of the properties reaches its maximum or even regresses. Tables 1 and 2 give a typical formulation and properties for a latex concrete respectively [28, 29].

4.2. Bandages

As for the bandages repair, the use of cementing matrices reinforced with polypropylene fiber is well recommended.

4.2.1. Surface preparation

- Prick all the disaggregated and removed concrete along the whole bandage length until reaching the concrete centre;
- Rinsing and blast cleaning of all the concrete surfaces;
- Remove all the corrosion products from the reinforcement bars using sand blasting;
- Clean the non-exposed bars, using metallic brushes;
- Coat the corroded reinforcements, using an anti-corrosion product generally in the form of pre-proportioned kit composed of a resin and a hardener [28].

Table 2 Properties of polymer cement concrete and Portland cement concrete [29]

Material	Tensile Strength, MPa	Modulus of Elasticity, GPa	Compressive Strength, MPa	Shear Bond Strength, KPa	Water Sorption, %	Freeze-thaw Resistance, No. of Cycles/ % Wt. Loss	Acid Resistance*
Polymer cement concret	5.6	14	38	$\geq$ 4,550	–	–	4
Portland cement concret	2.5	24.5	35	875	5.5	700/25	–

*Improvement factor in relation to Portland cement concrete.

4.2.2. Latex based mortar

The durability of mortar depends not only on the mortar mix itself but on the environmental conditions encountered during its service life. In this study, a latex based mortar reinforced with the polypropylene fiber was used for the bandages repair. In general, the latex content varies between 10 and 20% in respect to the cement mass. The latex addition gives a good adherence to the support. It gives also the impermeability and the improvement in protection of the reinforcement, thus resistance to chemical attacks.

Fig. 5 Multi-directional cracking of the concrete. After repair.

5. Bridge state after repair

The second part of the present work concerns the study of the bridge state after 4 years since its repair. It has been observed practically the same type of degradation for the bandages despite the removal of the hidden walls. The gutter-spouts have not been widened narrow and what's more most of them still blocked! However, the piers showed no sign of degradation. Apparently, it's much easier to do repair work on vertical structures like the piers than on horizontal ones like the bandages. It's worth noting that the traffic has not been stopped during the repair period and this certainly didn't help things much.

5.1. Bandages

The bandages are mostly affected, mainly at their ends. The degradations started by the cracks formation at the end of all the bandages. These cracks are as large as 10 mm.

Some of the bandages have shown cracks in all directions, Fig. 5. The formation of these cracks is certainly due to the reinforcement corrosion which arises from the fact that the work repair had not been carried out properly, poor corrosion product removal during repair.

The removal of the corrosion product must be done properly. If this is not the case, it's possible that the corrosion process will continue after repair, especially in the case of chloride induced corrosion as in our case. Special care must be taken to ensure the cleaning efficiency. This has not been done because of probably the difficulties encountered during repair. Besides, the mortar layer used was very thin, only the degraded part concrete has been replaced. What have caused and accelerated the corrosion phenomenon was the rain water flow through the pavement joints which were not so tight, Figs. 6 and 7.

We noticed that where there are signs of water flows, the degradations were very significant indicating that the rain water is still very aggressive.

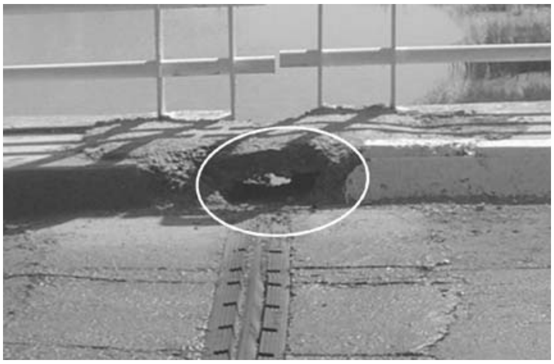

Fig. 6 A non tight joint.

Fig. 7 Heavy water flow traces indicating very poor jointing and defective rain water.

5.2. Piers

The piers are not affected.

6. Inspection and maintenance

An inspection program should be drawn for any work in service. And it's more urgent and a must for a work which had been already repaired like in our case. This program should include the following actions:

- Reckon in time the work damages and determine the degradation origins;
- Establish a technical file for the work from observations;
- Provide the data for maintenance;
- Take urgent measures.

7. Conclusions

The primary issues of the concrete repair project deal with the evaluation of the condition of existing structures to be repaired, repair solutions, and additional protection of embedded reinforcement.

This paper presents the results of a diagnostic and repairs realized on a reinforced concrete bridge as well as the bridge state after repair. The objectives of this study were mainly to determine the causes of degradation of the bandages and the piers of the bridge and also to highlight the importance of the maintenance and inspection of the work. The results of this investigation converge towards a chemical attack by the chloride ions which caused the corrosion of the reinforcements leading inevitably to bursting of the concrete.

For bandages repair, a latex based mortar reinforced with polypropylene fiber has been used whereas a latex concrete has been used for the piers repair.

Four years after repair, practically, the same disorders were noticed on the work mainly cracking of the concrete and corrosion of the reinforcements causing the bursting of the wrapping concrete. These degradations were observed particularly at the bandage ends where there are signs of water flows due to a poor jointing. It is important therefore, for the engineer undertaking the design of repairs and structures strengthening, to have an overall strategy, similar to the ones used during design.

The premature corrosion of repaired concrete structures is dependent not only on materials, techniques, and systems used, but also on the quality of workmanship as well as on the right approach to repair right from the beginning.

Poor repair work design and on-site practices, and indifference to quality control during the repair installation, often produce a final product of dubious quality.

References

1. Elsner BM (2002) Corrosion of steel in concrete—implications for corrosion monitoring. Cement & Concrete Composites 24:65–72.
2. Schiessel P (1988) Corrosion of steel in concrete, RILEM Technical Commitee 60-CSC. New-York: Chapman & Hall.
3. Andrade C, Alonso C, Sarria J (2002) Corrosion rate evolution in concrete structures exposed to the atmosphere. Cement and Concrete Composite 24:55–64.

4. Lopez W, Gonzalez JA, Andrade C (1993) Influence of temprtature on the service life of rebars. Cem Conc Res. 23:1130–1140.
5. Nilsson LA (1997) Assessing moisture conditions in marine concrete structures. In: Blankwll A, editor. 26–30 May; Svolvaer, Norway. Norland: Norwegian Public Road Administration. pp. 273–282.
6. Liu T, Weyers R (1998) Modelling the dynamic corrosion process in chloride contaminated steel in concrete structures. Cem. Conc. Res. 28:365–379.
7. Montemor MF (2003) Simões AMP. Ferreira MGS Chloride-induced corrosion on reinforcing steel: from the fundamentals to the monitoring techniques. Cem. Conc. Res. 25:491–502.
8. Tatematsu H, Sasaki T (2003) Repair materials system for chloride-induced corrosion of reinforcing bars. Cem. Conc. Res. 25:123–129.
9. Gonzalez JA, Andrade C (1982) Effect of carbonation, chlorides and relative humidity on the corrosion of galvanised rebars embedded in concrete. Br. Corros. J. 17:21–28.
10. Tulliania JT, Montanaroa L, Negroa A, Collepardi M (2002) Sulfate attack of concrete building foundations induced by sewage waters. Cem. Conc. Res. 32:843–849.
11. Bickley JA (1999) The repair on arctic structures damaged by thaumasite. Cem. Conc. Res. 21:155–158.
12. Mather B (1968) Field and laboratory studies of the sulphate resistance concrete. In: Swenson EG, editor. Performance of concrete. University of Toronto Press; pp. 66–76.
13. Cohen MD (1983) Theories of expansion in sulfoaluminate-type expansive cement: Schools of thought. Cem. Conc. Res. 13:809–818.
14. Browne RD (1980) Mechanisms of corrosion of steel in concrete in relation to design. Inspection and repair of offshore and coastal structure. ACI SP-65.
15. Vaysurd AM, Emmons PH (2000) How to make todays repairs durable for tomorrow corrosion protection in concrete repair. Construction and Building Materials 14:189–197.
16. Andrade C, Gonzalez JA (1978) Quantitive measurements of corrosion rate of reinforcing steels embedded in concrete using polarization resistance measurements. Werkst. Korros. 29:515–519.
17. Gonzalez JA, Andrade C (1982) Effect of carbonation, chlorides and relative humidity on the corrosion ofgalvanized rebars embedded in concrete. Br. Corros. J. 17:21–28.
18. Hansson CM, Mammoliti L, Hope BB (1998) Corrosion inhibitors in concrete: Part I. The principles. Cem. Conc. Res. 28:1775–1781.
19. Mammoliti L, Hansson CM, Hope BB (1999) Corrosion inhibitors in concrete: Part II. Effect on chloride threshold values for corrosion of steel in synthetic pore solutions. Cem. Conc. Res. 29:1583–1589.
20. Emmons EH, Vaysburd AM, McDonald JE (1993) A rational approach to durable concrete repairs. Concr. Intern. 15:40–45.
21. Roberty P, Shaw J (1997) Materials for the repair and protection of concrete. Construction and Building Materials 11:275–281.
22. Larrard FD, Bouny VB (2000) Vieillissement des bétons en milieu naturel. Bulletin des Laboratoires des Ponts et Chaussées 51–65.
23. Taché G et Vié D (1998) Diagnostic des ouvrages en béton armé, facteurs de vieillissement des ouvrages. Annales du Bâtiment et des Travaux Publics 27–37.
24. Poineau D (1994) Origine des pathologies, observation, diagnostic dans les ouvrages d'art. Bulletin de Liaison des Laboratoires des Ponts et Chaussées 97–124.
25. Baron R (1992) La durabilité des armatures et du béton d'enrobage. Presses de l'ENPC 173–225
26. Dhir RK (1993) Concrete: chloride diffusion rates. Mag. Con. Res. 1–9.
27. Jonathan GMW (1993) Quelques expériences étrangères en matières de prévention et de diagnostic: spécification pour des grands: pont, tunnels et barrages. Annales de ITBTP 3–20.
28. Baron J, Ollivier JP (1997p) Les bétons bases et données pour leur formulation. Paris: Eyrolles; 522.
29. Blaga A, aBeaudoin JJ (1985) Polymer modified concrete. Canadian Building Digest – CBD-241 IRC-CNRC.