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Case Study of a Damaged Reinforced Concrete Bridge

Etude d'un cas de détérioration du béton d'un pont

Untersuchung der Ursachen des Betonverschleisses einer Brücke

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SUMMARY

This paper presents the results of an inspection carried out in one bridge built 50 years ago, aiming at identifying the origins of general concrete cracking. The results of the observations and tests made it possible to conclude that the cracking was due to alkali-silica reactions. Subsequently, the corrosion of the reinforcing steel caused larger cracks and concrete spalling.

RÉSUMÉ

Ce travail présente les résultats d'une inspection réalisée sur un pont construit il y a 50 années, afin d'identifier les causes de la fissuration généralisée du béton. Les résultats des observations et des essais effectués ont permis de conclure que la fissuration du béton a résulté des réactions alcali-silice. Postérieurement, la corrosion des armatures a provoqué le développement de la fissuration et l'éclatement du béton.

ZUSAMMENFASSUNG

In dieser Arbeit werden die Ergebnisse einer an einer Brücke vorgenommenen Inspektion dargelegt, die vor etwa 50 Jahren gebaut wurde, um die Ursachen für das allgemeine Aufbrechen des Betons festzustellen. Die Ergebnisse der durchgeführten Untersuchungen und Tests lassen darauf schliessen, dass der Beton aufgrund von Alkali-Silika Reaktionen gerissen ist. Später sind die Risse breiter geworden, und infolge von Korrosionsphänomenen bei den Bewehrungen ist es zur Ablösung von Beton gekommen.

1. INTRODUCTION

The main cause of deterioration in reinforced concrete structures in Portugal is corrosion of the reinforcing bars, started by the attack of chlorides or by the carbonation of concrete. Known cases about the occurrence of expansive reactions in concrete have only been observed in marine structures and dams. In the first case, due to the attack of sulphates [1], in the latter, due to alkali-silica reactions, since silicious aggregates were used [2]. The deterioration due to the formation of secondary ettringite as reported by Brouxel and Hantzo [3], was not yet observed by us.

In this case, the preliminary inspection of the structure seemed to suggest that the corrosion of the reinforcing steel, due to chlorides or carbonation, might have been the primary cause of cracking, as a limestone coarse aggregate was used. However, the results of the tests carried out have pointed to the existence of alkali-silica reactions, the resulting cracking causing thus subsequent corrosion of the rebars.

2. ELEMENTS CONCERNING THE STRUCTURE

The Duarte Pacheco bridge, built in the 40's, is located in the Alcântara valley, a short distance from the Tagus estuary, in Lisbon. It is made up of a central arch with a span of about 100 m, linked by two 85 m long transition portal frames to two lateral arches with a 43 m span each (Fig. 1).

Almost all the information on the structure was lost. It is however known that in manufacturing the concrete coarse limestone aggregate from the region, natural silicious sand and ordinary portland cement were used. The geological information later obtained states that the limestone from the Lisbon area is from the cretaceous, where flint formations are often present, either in the form of inclusions, at times microscopic, or in the form of layers of small thickness not exceeding 10 mm.

3. INSPECTION METHODOLOGY

The general methodology adopted for inspecting the concrete was basically the one recommended by ACI [4], as indicated below:

- Data collection on the bridge construction;
- Preliminary inspection with a view to identifying the problem and defining a detailed inspection plan;
- Detailed visual inspection in order to identify the various types and extents of deterioration in the concrete;
- Carbonation tests, potential corrosion measurements and core drilling for lab tests;
- Lab tests on collected samples, namely chlorides and sulphates contents, examination and compressive strength of cores, SEM/EDX and X-ray diffraction tests;
- Identification of the causes of concrete deterioration.

4. OBSERVATIONS AND TEST RESULTS

4.1 Visual Inspection

The different levels of deterioration found in concrete were characterized as follows [5]:

- Disperse cracking almost imperceptible to the naked eye;
- Disperse cracking or aligned cracking following the main reinforcing bars, less than 0.1 mm wide;

- Disperse cracking or aligned cracking following the main reinforcing bars, about 0.1 mm wide;
- Disperse cracking or aligned cracking following the main reinforcing bars, about 1 mm wide, without concrete spalling;
- Disperse cracking or aligned cracking following the main reinforcing bars, some millimeters wide, with different stages of concrete spalling;
- Localized spalling of the concrete.

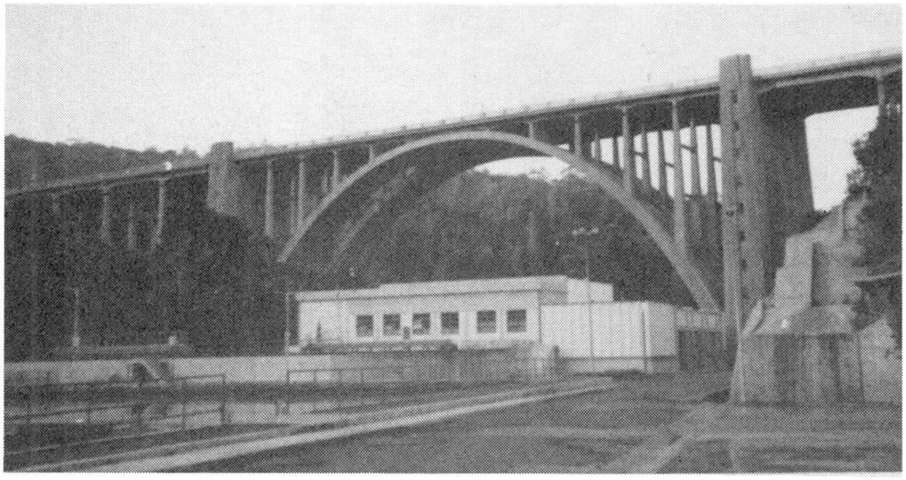


Fig. 1 General view of the bridge

The areas of greater deterioration were located in the central arch, below which the road traffic is more intense, in places more exposed to rain and sunshine. Figs. 2 and 3 show typical examples of cracking observed in concrete.

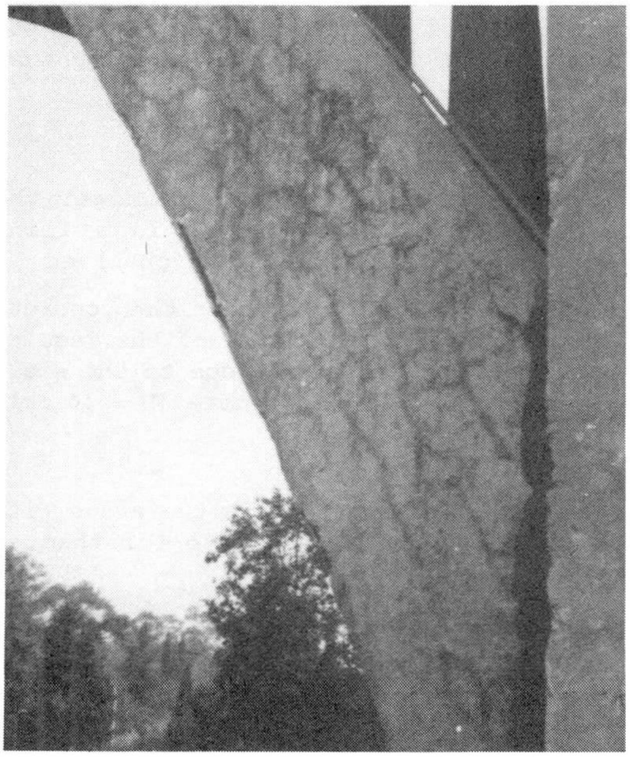


Fig. 2 Central Arch, southern view. Map cracking

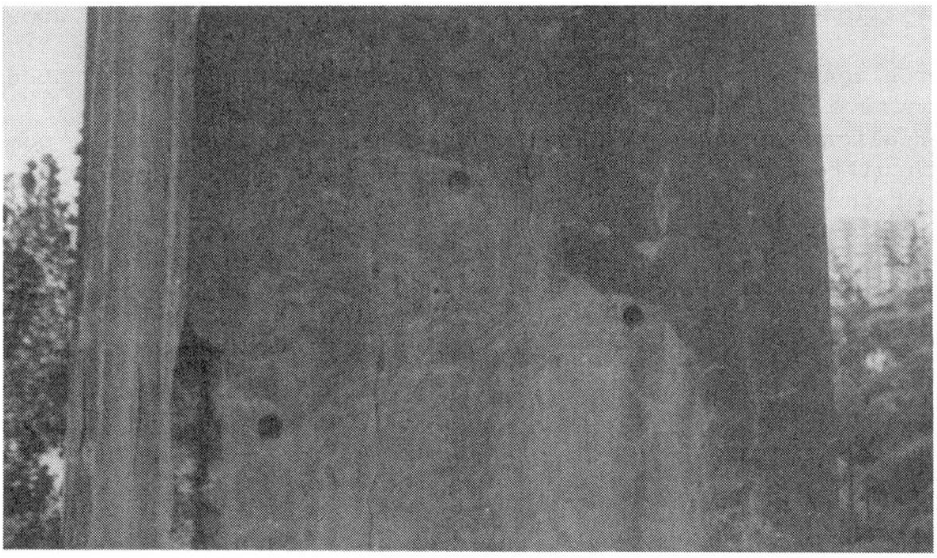


Fig. 3 Column of the Central Arch, facing the south. Cracking aligned with the main reinforcing bars

4.2 Depth of carbonation

The results show that the depth of carbonation was generally less than 10 mm, never exceeding 15 mm.

4.3 Penetration of chlorides and sulphate content

The tests were carried out in laboratory on powder samples taken by a diamond drill from the same places where the carbonation depths were measured.

It was observed that the penetration of chlorides at 10 and 20 mm depths, respectively show maximum contents of 0.15% and 0.07%, in relation to the concrete weight. Considering a cement content of 400 kg/m^3, it can be seen that even for a 20 mm depth the chlorides content is in most cases less than the maximum limit allowed by ENV 206 (0.4% of the cement weight). Mention must be made of the fact that the average chlorides content, expressed in relation to the cement mass is 0.39% and 0.19% at 10 and 20 mm depths, respectively.

As regards to sulphates, results of 4.5% and 1.5% were obtained in relation to the cement weight, respectively for the same 10 and 20 mm depths. It may be noted that there is an increase of sulphates near the surface.

4.4 Examination and compressive strength of cores

The visual inspection of cores, after air drying of the surface, showed the existence of wet areas around flint particles. A crack beginning in a flint particle, at a 80 mm depth, developing towards the surface, was also observed.

The strength tests carried out on cores with $h = d = 45$ mm showed that the concrete presented an average compressive strength of 70 MPa. The dispersion of the results was fairly high, with values ranging from 41 MPa to 96 MPa, mainly due to the small diameter of the cores, compared with the maximum size of the aggregate ($D = 40$ mm).

4.5 Corrosion potentials

It was observed that the corrosion potentials were more negative in the areas with greater cracking. The values were not however sufficiently negative for them to indicate active corrosion on the steel surface.

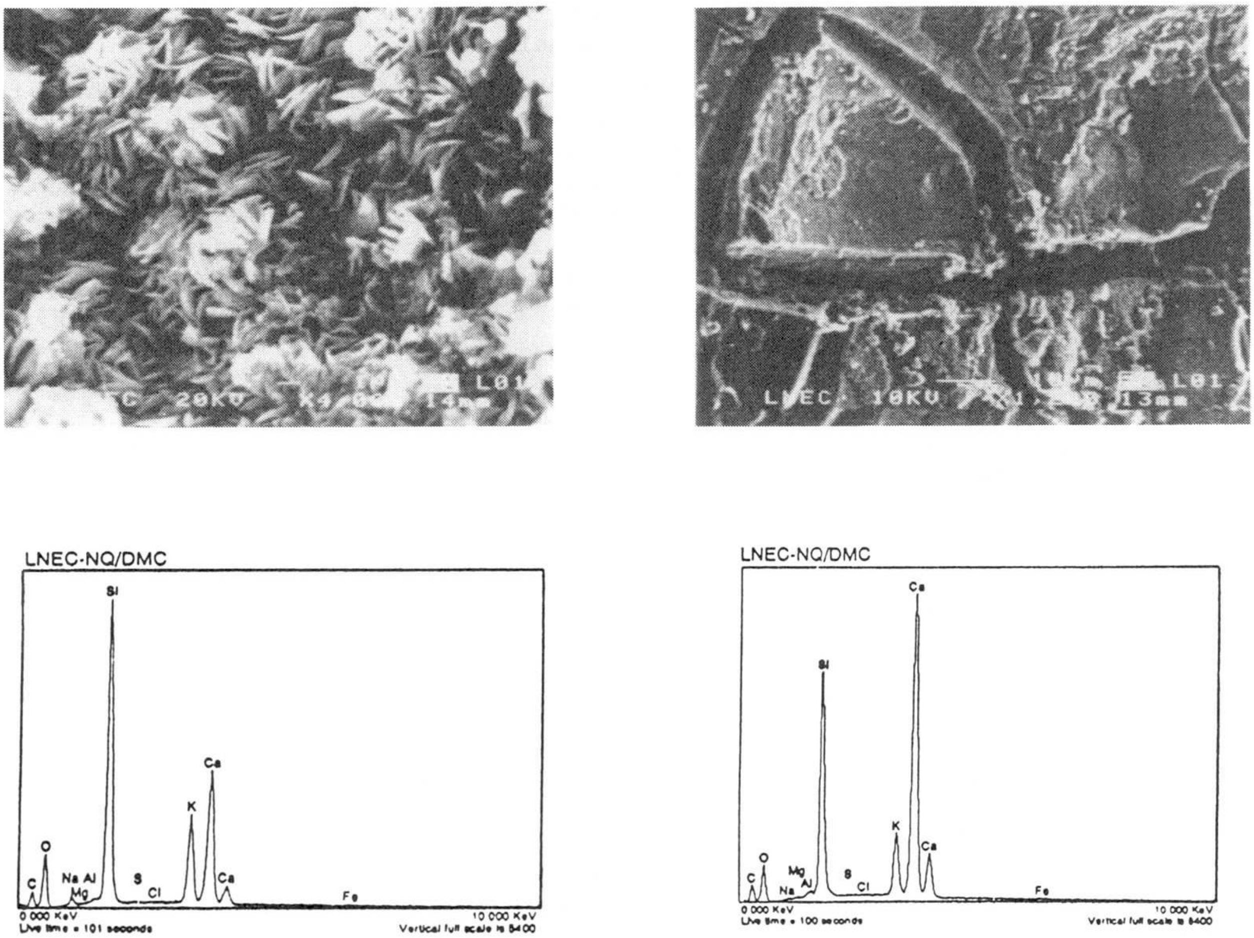
4.6 SEM/EDX tests

Scanning electron microscope (SEM) observations and energy-dispersive X-ray (EDX) microanalysis in the steel/concrete interfaces of some samples taken from the

Central Arch, showed the absence of chlorides and the presence of a high number of ettringite agglomerates, both in a massive or acicular crystals forms.

Observations were also carried out on other samples taken from more cracked areas of the Central Arch. These observations showed in limestone/paste interfaces the presence of typical compounds of alkali-silica reaction (Fig. 4), such as hydrated calcium and potassium silicates (crystalline and amorphous), as well as ettringite, either in the characteristic form of acicular crystalls, or in a massive form. Other authors [6] have observed similar morphologies in the presence of alkali-silica reactions.

The X-ray microanalysis of the alkali-silica reaction products showed that the crystalline products are less rich in calcium (Ca) than the amorphous ones. The occurrence of ettringite in cracks, pores and slightly disperse in the paste was also observed.



a) b)

Fig. 4 Products of alkali-silica reaction (calcium and potassium silicates) in a limestone/paste interface.

a) Crystalline products and corresponding X-ray spectrum;

b) Cracked gel and corresponding X-ray spectrum.

4.7 X-ray diffraction analysis

The presence of ettringite in the paste was also confirmed by X-ray diffraction. In the samples corresponding to more cracked areas, sulphates in proportions slightly higher than those observed in samples from uncracked areas were detected.

The X-ray diffraction analysis of the coarse aggregate particles taken from the concrete indicated that they were mainly made up of calcite mineral with traces of quartz.

5. CONCLUSIONS

Carbonation induced corrosion is only relevant in certain areas, where the cover was small due to construction defects.

The low chloride content of concrete indicates that steel corrosion is not due to chloride attack. The non-existence of chlorides in the rebar corrosion products, as showed by SEM observations, reinforces this conclusion.

The results on the corrosion potentials did not show, even in more cracked areas, the existence of active corrosion at the steel surface.

The visual observation of cores, the results of the SEM/EDX tests, and the X-ray diffraction analysis, suggest that the concrete cracking results from the alkali-silica reactions between the alkalis of cement and reactive silica inclusions of limestone aggregate. A slight attack by sulphates of external origin, resulting from the atmospheric pollution (SO_2) may also be present. Subsequently concrete cracking, may have provided, in some places, the conditions for depassivation of the reinforcing steel and the consequent emergence of corrosion, causing thus the increase of cracks width and concrete spalling.

6. ACKNOWLEDGMENTS

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