

Degradation of Concrete Bridges by Internal Expansive Reactions – Portuguese Case Studies

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Abstract

In the last years some concrete bridges in Portugal have shown premature deterioration due to intensive concrete cracking development mainly attributed to internal expansive reactions. An important experimental program was conducted by Laboratório Nacional de Engenharia Civil (LNEC), a public institution of the Portuguese Ministry for Public Works, Transports and Housing, in order to diagnose the causes and also prognostic the long-term behaviour of the deteriorated concrete bridges.

The research conducted has pointeded that the concrete cracking was mainly due to the occurrence of internal expansive reactions: alkali-silica reaction (ASR) and/ or delayed ettringite formation (DEF).

The ASR was caused by the use of alkali reactive aggregates and the DEF by the high heat-curing temperature obtained during the setting and hardening in combination with the high portland cement content used in the concrete mix designs.

Residual expansion tests were done in order to access the residual ASR and DEF reactivity. Measurements have been carried out with the methods normally used for ASR and DEF concrete testing: $38^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and 95% HR in the first case and $20^{\circ}\pm 2^{\circ}\text{C}$ and 100% HR for the second. Mostly of the bridges show residual capacity to continue the expansion due to ASR or DEF, which forced remedial measures against these expansive reactions, mainly associated with control of the ingress of water into concrete.

This situation in Portugal led to conclude that new deterioration cases can occur. To avoid these causes of damage the design and construction of new structures must follow the new Portuguese preventive methodologies (developed by LNEC).

Keywords: Alkali-silica reaction, delayed ettringite formation, concrete, bridges, recommendations

1 – Introduction

In recent years have been discovered in Portugal several cases of reinforced concrete bridges damaged by internal expansive reactions (figure 1a). The number of cases is already significant enough to make known this disease and the methods to be used in the existing structures for its diagnosis, and the mitigation forms in the new structures.

This kind of degradation is due to alkali-silica reaction, caused by the use of alkali reactive aggregates (1), and to delayed ettringite formation, that is attributed to the high heat-temperature obtained during the setting and hardening in large massive structural elements of concrete in combination with high Portland cement contents (2). Several factors contributing to this situation, some related to the lack of rules and regulations, or simply by not implementing the recommendations where they remain effective.

The diagnosis of these degradation forms requires technical expertise since their symptoms in the structure, including the expansion of the material with the emergence of multi-directional cracking, are similar in both reactions. Moreover, is a task that can be tricky namely because the ettringite formation is also a product that normally occurs in healthy concrete (3)(4).

2 - Methods of diagnosis and prognosis

The methodology of diagnosis (3) is based on an assessment that must take into account the micro and macroscopical concrete characteristics, the former only related with the material and the second also with the structure type and the environmental exposure conditions (wetting-drying cycles, permanent immersion etc.). The collection of historic information on the composition and application conditions of concrete is also very useful because they can be related to the degradation pathology.

Laboratory tests performed on concrete cores taken from the structure is the basis of diagnosis in this type of degradation. This must require the extraction of concrete cores in cracked and sound zones. It should be noted that the samples should be deep enough to be representative of the maximum temperatures reached in the concrete elements. Otherwise, the material is likely to not show the presence of degradation products, which may be present in the interior and misleading the conclusions. Microscopical methods, using optical (MO) and scanning electron microscopy (SEM), are the only techniques to identify the products resulting from ASR and DEF – figures 1b and 1c.

The prognosis of the future behaviour of a concrete affected by DEF and ASR is a very important task since it could be used to prioritize the structure mitigation/repair needs. This implies the realization of additional tests for evaluation of the concrete residual expansion performed in cores taken from the structure. The recommended diameter of the cores is 100 mm, and the length of the core must be also representative of the interior of the concrete element (for massive elements the minimum length must be 600 mm). The extraction must be done in different zones of the structure, avoiding the interception with cracks or reinforcement bars.

The observation and measure of the cracks length and width is also an additional monitoring method to assess the development of ASR and DEF in the structure when the residual expansion tests give the indication that potential for future expansion exist. However, this assessment must be carried out in a precise, reliable and reproducible way over time (5).

3 – Case studies

The case studies here presented where this methodology was applied will be reported by a code due to reasons of confidentiality. They are two reinforced concrete bridges where the degradation occurred mainly in the massive elements of the structure.

3.1 – Bridge A

This reinforced concrete bridge was built in the late 70's and is located in centre of Portugal. With the exception of extreme piers, all the piers are immersed in the river water, in some cases several tens of meters. It is visible an intense map cracking on all the piers in contact with water and in the zones of the deck beams exposed to rain water. It should be noted that water is one of the key factors that promote the development of these expansive reactions.

In this case study a simple macroscopic observation of the cores taken in the most cracked zones of the structure, reveals the occurrence of products filling pores and in the aggregate-paste interfaces (figure 2a), which is a important feature normally associated to internal expansive reactions. The optical and electronic microscopical observations confirmed the degradation cause is ASR and DEF (figure 2b), which in this case was a consequence of the use of alkali-reactive siliceous aggregates and the relatively high cement (CEM I) content employed ($>350 \text{ kg/m}^3$).

For prognosis of future concrete performance, expansion tests were performed on cores obtained from different structural members in order to determine the concrete residual expansion. Since the diagnostic concludes about the occurrence of ASR and DEF, two different tests, specified to each expansive reaction, were conducted (6-10). The results obtained showed that exist potential for future concrete expansion due to ASR, and also to DEF but only in the pier pedestal. In the other structural elements no potential exist for future concrete expansion due to DEF. This kind of evaluation could support the decisions on the application of different repairing methods in the distinct parts of the structure.

3.2 – Bridge B

This reinforced concrete bridge was built in the end of 90's and is located in the northern region of Portugal. In the concrete production granite and siliceous aggregates from local quarries and high content of cement (CEM I $> 400 \text{ kg/m}^3$) were used.

After 10 years in service, it was detected the presence of extensive map-cracking in some piers and in the massive cap piles. The cracking pattern induced the suspicion of internal expansive reactions occurrence in the concrete - figure 3a.

The diagnosis tests showed the presence of ASR, due to the use of alkali reactive granite aggregates, and also DEF. The DEF has been associated with the high cement content and also to very massive structural elements. Note that the combination of ASR with the DEF could be simultaneously, since the ettringite is not stable in concretes with high alkali contents. In these conditions, the sulfate ions do not have been combined during the setting of the concrete and are available in the interstitial solution of concrete to precipitate later as delayed ettringite.

Prognosis tests to ASR and DEF indicated that there is potential for further expansion of the concrete and that this potential is greater in areas where there is greater thickness of concrete. This finding is extremely important for the prioritization and selection of means of intervention.

4 – Conclusion

The internal expansive reactions (ASR and DEF) are a problem of durability of concrete structures requiring the adoption of appropriate methodologies for its diagnosis and prognosis. This paper presents a methodology of diagnosis and prognosis that explains the degradation causes, allows to predict the evolution of the phenomenon and its consequences for the structure and supports the decisions taken about the repairing options in the structure elements.

The case studies presented show that this disease affects mainly massive elements and concretes with high cement contents. Furthermore, the cements used do not contain any type of mineral pozzolanic additions (fly ash, metakaolin, etc.).

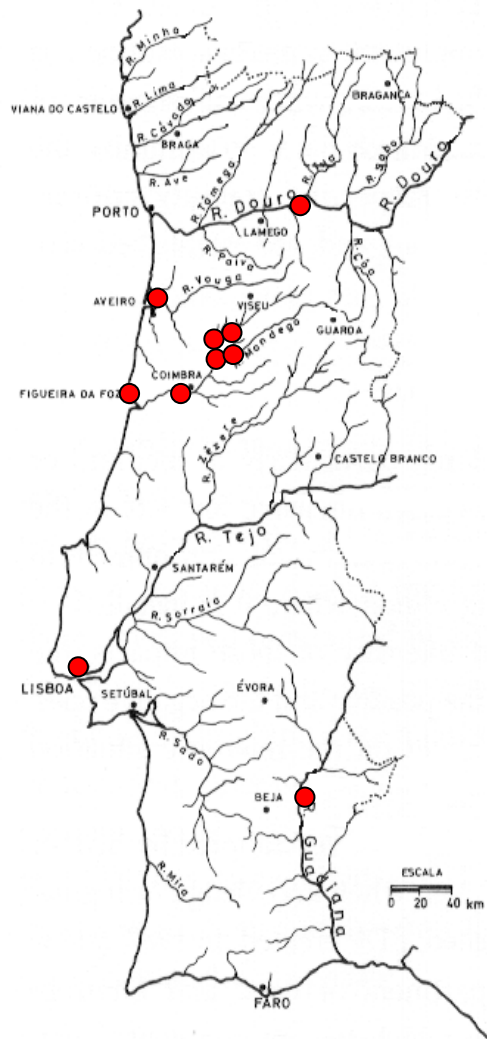
Today is well known that one of the mitigation measures of ASR and DEF during the design and construction of new structures is the use of type II additions, with or without cement replacement. The performance of each addition in the mitigation of these reactions depends on its content and pozzolanic activity. In order to verify the long-term behaviour of different mineral additions in the mitigation of these expansive reactions in concrete an important experimental program is being conducted by LNEC.

Acknowledgments

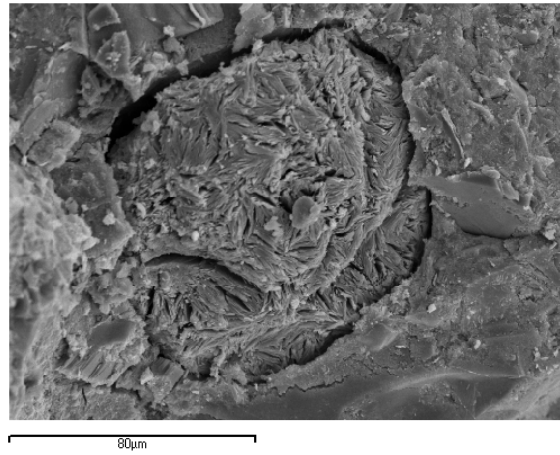
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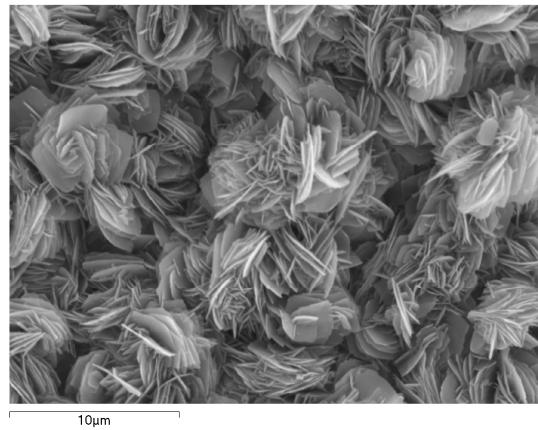
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a)



b)

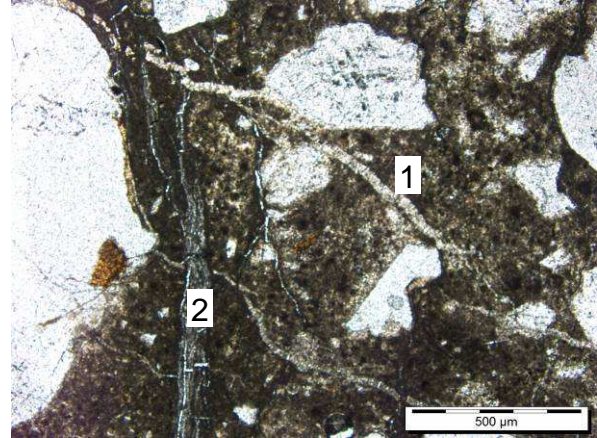


c)

Figure 1 – a) Simplified map of Portugal with the locals of some reported cases of concrete bridges affected by ASR and DEF; b) SEM image of a concrete showing a pore in the cement paste filled by DEF; c) SEM image of ASR products in a concrete.



a)

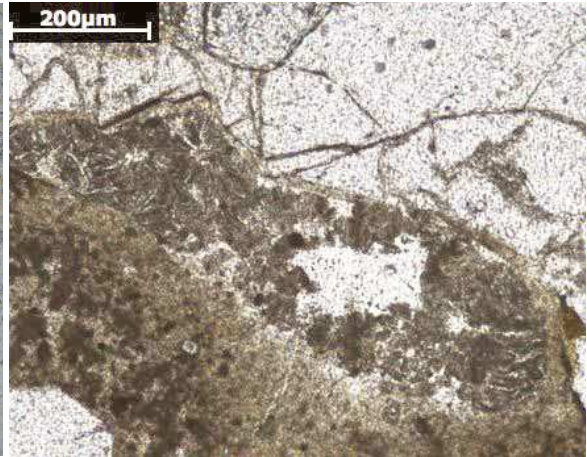


b)

Figure 2 – a) Detail of a concrete core showing the presence of with products filling voids and aggregate/paste interfaces; b) Image obtained at polarizing microscope of a concrete thin section showing the presence of veins of DEF (1) and ASR gels (2) along the paste.



a)



b)

Figure 3 – a) Detail of the map-cracking in a concrete pile cap; b) Image of the concrete at petrographic microscope showing a void with an irregular shape partially filled with DEF near a aggregate/paste interface.