Concrete bridges affected by internal swelling reactions: reactions mitigation and structural rehabilitation

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Abstract. The increasing number of bridges affected by internal swelling reactions in concrete has raised significant concerns among bridge owners, given the serious consequences for their durability, serviceability and safety, which may involve high repair costs or even the replacement of severely damaged structures. This paper aims to provide an overview of the procedures used to prevent these reactions, with a particular emphasis on the methods used to mitigate their effects in affected bridges. Additionally, some examples of solutions applied to Portuguese bridges are presented.

1 Introduction

Internal swelling reactions in concrete have been increasingly affecting a wide range of structures. Currently, there are records of these reactions occurring in various types of construction, including railway sleepers, dams, bridges, buildings, nuclear power stations, as well as road and airport pavements.

There are primarily two types of internal swelling reactions (ISR) in concrete: alkali-aggregate reaction (AAR) and delayed ettringite formation (DEF). The occurrence of any of these reactions leads to the formation of compounds with expansive properties, which cause cracking and can result in a significant loss of stiffness and strength in the concrete.

In the case of bridges, this problem has generated growing concern among infrastructure managers due to its impactful consequences, involving high repair costs or even the replacement of deeply affected bridges.

This paper aims to provide an overview of the procedures used for the prevention, diagnosis, and prognosis of these reactions, with a primary focus on the methods employed to mitigate their effects on affected bridges.

2 Internal swelling reactions

2.1 Alkali-Aggregate Reactions

Alkali-aggregate reaction (AAR) in concrete is a chemical reaction that occurs between the alkali hydroxides present in Portland cement and certain reactive minerals found in some aggregates, especially when moisture is present. This reaction can produce a hygroscopic gel that absorbs water and expands, leading to internal pressure, cracking, and, over time, significant deterioration and loss of strength in the concrete structure. The most common form of AAR is the alkali-silica reaction (ASR), where the alkalis react with non-crystalline silica in the aggregates to form an expansive gel. Less commonly, alkali-carbonate and alkali-silicate reactions can also occur, involving different types of reactive aggregates.

2.2 Delayed ettringite formation

Delayed ettringite formation (DEF) in concrete is a chemical process where the mineral ettringite forms within hardened concrete, rather than during the initial setting and hardening phase. This delayed formation is typically triggered when concrete is exposed to high temperatures (usually above 65 °C) during cement early hydration. Once the concrete cools and is subsequently exposed to moisture, ettringite forms and expands within the hardened matrix, leading to internal stresses, cracking, and potential structural damage. DEF is most commonly observed in heat-cured precast elements and large *in situ* pours where high internal temperatures are reached. The main consequences of DEF are expansion, cracking, and a reduction in the durability and structural integrity of the affected concrete.

2.3 Structural effects

AAR and DEF, although different, as mentioned above, have similar effects on structures. In fact, both the hygroscopic alkaline gel resulting from AAR and delayed ettringite expand in the presence of water, giving rise to internal stresses that cause cracking when they reach the concrete's tensile strength, and other damage to structures. This damage typically becomes apparent 5 to 10 years after construction, usually in areas most exposed to water.

Cracking caused by expansive reactions is characterised by an irregular crack pattern, sometimes described as "craquelé". However, the confinement due

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to prestressing or high axial loads tends to orient cracks in the direction of principal confinement.

Fig. 1. Irregular cracking pattern caused by ISR.

The expansion of the concrete can be seen in the closure of expansion joints (Fig. 2) and in the displacements of the support devices.

Fig. 2. Closed expansion joint.

In addition, surface discolouration of the concrete, gel exudation or surface disintegration of the concrete can be seen in the affected structures.

3 Prevention in new structures

Prevention of swelling reactions in concrete relies on removing at least one of the essential conditions required for their occurrence. For the AAR to develop, the essential factors are, as mentioned above, the use of sufficient reactive aggregates, high levels of alkalis in the concrete's pore solution and high humidity. The prevention of DEF can be achieved by maintaining moderate temperatures during the hydration of concrete (below 65 ºC), avoiding high levels of alkalis, aluminates or sulphates in the cement, or by avoiding contact with water.

Extensive research has led to significant recommendations and testing methods to quantify and limit these effects [1]. Many national bodies have published guidelines and standards for selecting concrete components and mix design, tailored to available materials, structure type, and exposure conditions [2,3,4,5,6,7,8]. These documents are regularly updated as new knowledge emerges. In Portugal, LNEC released the first edition of E 461 specification [9], in 2004, subsequently revised in 2007, and significantly restructured in 2021, to incorporate international advancements, duly adapted to the characteristics of Portuguese materials [10].

Thanks to the progress in this field, expansive reactions are now unlikely in new constructions, provided that recommended preventive measures are followed.

4 Mitigation in existing structures

4.1 Overview

Mitigating the effects of internal expansive reactions in affected structures has attracted significant attention from the international technical and scientific community. The term "mitigation" is used because interventions in these cases aim to reduce future expansion or lessen its harmful impact, rather than restore the original properties or integrity of the affected structure.

Mitigation and repair differ fundamentally in their objectives and approaches when managing internal expansive reactions in concrete structures.

Mitigation focuses on reducing or slowing future expansion and minimising the harmful effects of ongoing reactions. It does not aim to restore the structure to its original state but instead seeks to limit further deterioration. Typical mitigation actions include reducing moisture ingress, applying surface treatments, or modifying environmental conditions to slow down the reaction.

Repair, on the other hand, involves interventions designed to restore or improve the original properties, appearance, or integrity of the structure. This may include crack filling, sealing, structural strengthening, or even partial replacement of damaged concrete. Repair addresses the symptoms and damage already present, rather than the underlying cause of ongoing expansion.

Various approaches have been adopted, but there is no consensus on the best method due to the wide range of situations – both in terms of the characteristics and development stage of the reactions, as well as the types of structures and environmental conditions involved.

4.2 Prevent water or humidity from penetrating the structures

Environmental control can help mitigate the effects of expansive internal reactions in concrete structures primarily by managing moisture levels. Since high humidity or the presence of water is essential for the progression of reactions like alkali-aggregate reaction (AAR) and delayed ettringite formation (DEF), reducing or eliminating moisture ingress is one of the most effective mitigation strategies. This can involve:

- Improving drainage around structures to prevent water accumulation.
- Applying surface sealants or coatings to limit water penetration.

- Controlling indoor humidity through ventilation or dehumidification.
- Designing structures to minimise direct water exposure.

By targeting environmental factors, especially moisture, these measures can significantly slow or halt the progression of expansive reactions, thereby reducing further damage and prolonging the service life of affected structures.

4.3 Mechanical means to confine the expansion or to release the constraints

The expansion caused by expansive reactions is strongly conditioned by the confinement provided by reinforcement, as well as by the stress fields resulting from applied loads or prestressing. Expansion decreases with increasing confinement, and cracks tend to orient themselves in the direction of the highest confinement stresses.

In the case of alkali-aggregate reaction (AAR), when expansion is restrained in one direction, expansion increases in the directions with less confinement. For delayed ettringite formation (DEF), confinement in one direction does not cause a significant rise in expansion in the less confined directions; instead, there is a systematic reduction in the overall expansion volume compared to concrete that is allowed to expand freely.

Mitigation techniques based on concrete confinement involve the application of passive or active elements, depending on whether non-tensioned or tensioned elements are used.

Passive elements can be realised using, for example, concrete components, steel bars or plates, fibre-reinforced polymer (FRP) sheets or strips. These advanced composite materials have been increasingly used in the rehabilitation of structures, specifically in bridges affected by swelling reactions. Not only are they an effective solution for limiting expansion, although it doesn't eliminate it completely, but they also have the added advantage of being waterproof.

4.4 Chemical or electrochemical means

The modification of the properties of the formed gel, so that it is not expansive, is one of the possible preventive measures against the deleterious occurrence of AAR. This measure is based on the fact that the presence of certain lithium salts, such as lithium carbonate or lithium nitrate, modifies the characteristics of the gel formed in the reaction, eliminating its expansive properties [11]. Laboratory tests have shown that affected concrete specimens can be treated using lithium-based compounds to slow down the expansion rate [12], but the main challenge is achieving adequate lithium penetration, especially if the concrete porosity is low, with reports of experiments in which the reduction in expansion was not significant [13].

The treatment of structures with lithium is, therefore, a technology still under development, whose application to real structures cannot yet be recommended systematically.

4.5 Replacement of the structure

Partial or total replacement of a structure affected by expansive reactions is a safe solution, but it is usually very costly. In most cases, there is an alternative solution to mitigate the effects of expansive reactions in a structure; however, there are situations where the advanced state of degradation or the complexity of applying these mitigation alternatives make partial replacement of the structure necessary, or, as a last resort, its total replacement.

Partial replacement is naturally less intrusive and more sustainable, allowing the structure's service life to be extended and providing a generally more economical solution. Therefore, it should be studied preferably, especially when the degraded concrete is in a confined area. The need to keep the project operational may hinder the implementation of this alternative.

This type of solution has already been applied to some Portuguese bridges [14].

5 Final remarks

The identification of signs of internal expansive reactions should prompt a careful process of monitoring this development. This process should include periodic inspections and measuring the evolution of the anomalies identified [15]. In addition, laboratory tests should be carried out on cores extracted from the structure, to confirm the occurrence of expansive reactions (diagnostic tests), determine how these reactions have affected the stiffness and strength of the concrete (mechanical tests) and predict the potential for these reactions to develop further (prognostic or residual deformation tests).

If the observations and experimental results obtained in situ, as well as laboratory tests, show the presence of expansive reactions, it is advisable to carry out a structural assessment, as well as a study to predict the future development of the structural effects of the reactions, through appropriate modelling of the structure. It is important, however, to distinguish between the case in which the reaction is exhausted and the case in which the reaction remains active.

In the first case, the situation is stabilised, it will be necessary to repair the structure to ensure its durability and, if necessary, restore its safety and functionality.

When the reaction remains active, the selection of measures to be taken depends, in addition to the state of degradation of the structure, on various factors, such as the residual expansion potential, the environmental conditions of the affected elements, the sensitivity of the structure to the expansion of these elements and the social and economic impact of a reduction in the bridge's level of service.

References

1. Lindgård, J., Nixon, P. J., Borchers, I., Schouenborg, B., Wigum, B. J., Haugen, M., & Åkesson, U.: The EU "PARTNER" Project - European standard tests to prevent alkali reactions in aggregates: Final results and recommendations. Cement & Conc. Research, 40(4), 611-635. (2010) https://doi.org/10.1016/j.cemconres.2009.09.004
2. AASHTO R 80: Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction, 25 pp. AASHTO, USA (2017)
3. ASTM C1778: Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete, 13 pp. ASTM, USA (2022)
4. BS 812-123: Testing Aggregates - Part 123: Method for Determination of Alkali-Silica Reactivity - Concrete Prism Method, 19 pp. BSI, UK (1999)
5. CSA A23.2-27A: Standard Practice to Identify Degree of Alkali-Aggregate Reactivity of Aggregates and to Identify Measures to Avoid Deleterious Expansion in Concrete, pp. 260–269. Canadian Standards Association, Canada (2019)
6. IFSTTAR (2018). Recommendations for preventing disorders due to Delayed Ettringite Formation. Marne-la-Vallée : IFSTTAR, Technics and methods, GTI5-A, 70 pages.
7. JIS A 1145: Method of Test for Alkali-Silica Reactivity of Aggregates by Chemical Method, 16 pp. Japanese Standards Association (2017)
8. JIS A 1146: Method of Test for Alkali-Silica Reactivity of Aggregates by Mortar-Bar Method, 13 pp. Japanese Standards Association (2021)
9. LNEC E 461: Concrete. Methodologies to Prevent Expansive Chemical Reactions of Internal Origin, 12 pp. LNEC, Lisbon (in Portuguese) (2021)
10. Custódio, J., Silva, A. S.: International Standards and Recommendations. In: Menéndez Méndez, E., Santos Silva, A. (eds) Total Alkalis in Concrete - Contribution to Alkali-silica Reaction. RILEM State-of-the-Art Reports, vol 40. Springer, Cham. https://doi.org/10.1007/978-3-031-56164-1_4 (2025)
11. Leemann, A., Bernard, L., Alahrache, S., & Winnefeld, F.: ASR prevention - Effect of aluminium and lithium ions on the reaction products. Cem. Concrete Research, 76, 192-201. https://doi.org/10.1016/j.cemconres.2015.06.002 (2015)
12. Guo, S., Dai, Q., & Si, R.: Effect of calcium and lithium on alkali-silica reaction kinetics and phase development. Cem. Conc. Research, 115, 220-229. https://doi.org/10.1016/j.cemconres.2018.10.007 (2019).
13. Folliard, K. J., Thomas, M. D. A., Fournier, B., Resendez, Y., Drimalas, T., & Bentivegna, A.: Evaluation of mitigation measures applied to ASR-affected concrete elements: preliminary findings from Austin, exposure site. 14th ICAAR (2012)
14. Rodrigues, T., Pereira, A. R., & Costa, A. M.: Reinforcement and replacement interventions in some bridges located on Angueira Dam Road Network. 16th International Conference on Alkali Aggregate Reaction in Concrete, Lisbon (2022).
15. Santos, L. O., Xu, M., & Silva, A. S. : Monitoring the structural effects of internal swelling reactions in Aguieira bridges. Proceedings of the Institution of Civil Engineers. Construction Materials, 1 14 (2022). https://doi.org/10.1680/jcoma.21.00046