Prioritizing criteria for intervention on Brazilian railway concrete bridges affected by chemical reaction

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Summary

Due to systematic chemical reaction cracks identified in concrete foundation pile caps of some railway bridges in southeastern Brazil, the concessionary developed a management plan with the main objective of maintaining the bridges in service. The strategy is to intervene annually in a greater number of bridges that present damage with the challenge of seeking technically viable solutions, enabling faster and more cost-effective while mitigating risks related to structural and durability issues. A comprehensive evaluation of the progression of the processes deteriorating the concrete elements was conducted, aiming to identify indicators that can be effectively monitored. As a result of the study, additional test procedures were performed on concrete extracted from the bridges, including the Damage Rating Index (DRI), the Stiffness Damage Test (SDT) and the cracking index (CI). These procedures were developed to assess both the current condition of the concrete and its potential for further expansion or distress due to chemical reactions. Based on the test results and the damage identified during inspection, assets are prioritized for intensified monitoring or interventions, depending on the risk level of each bridge as determined by the Bridge Management System (BMS). A maintenance ranking procedure was proposed to prioritize and define actions to be taken in each case. Examples of interventions carried out on railway bridges are also described.

1 ASSETS OF FERROVIA DO AÇO AND ITS CURRENT CONDITION

1.1 Description of bridges of Ferrovia do Aço

Ferrovia do Aço FA (it means “Steel” Railway) was constructed in 1970s, with operations starting in 1987. The primary purpose of this railway is the transportation of iron ore from terminal deposits in the State of Minas Gerais to connecting railways that lead to steel industries and the ports of São Paulo and Rio de Janeiro. The total extension of the FA Railway is 354km, featuring 110 bridges and 81 tunnels along the line.

The vast majority, 109 bridges of FA railway, are concrete bridges, with lengths ranging from 19m to 668m, and with spans around 25m. The average height of the bridge columns is around 30m, supported by concrete pile caps with average dimensions around 8m in plan and 3m height. The pile caps are normally supported by concrete piles with diameters of approximately 1.2m, and a number of concrete piles that can reach 30 in the same block.

Recently, Brazilian railways went through a privatization process, and since 1996, MRS Logística Company has been responsible for managing an extensive transportation network, that includes the FA Railway. Currently, the maintenance process of the FA Railways bridges is overseen by the concessionaire.

Fig. 1. A typical concrete bridge of Ferrovia do Aço (FA) Railway

1.2 Damages identified during structural inspections.

During inspections, typical damage caused by chemical reactions, such as mosaic-shaped cracks, has been observed in pile caps, columns and, more recently, in slabs of the FA Railway's concrete bridges. To diagnose these issues, petrographic analyses and scanning electron microscopy tests were conducted. The cracks were identified as Alkali-Aggregate Reaction (AAR) and Delayed Ettringite Formation (DEF).

Fig. 2. Typical cracks identified on concrete pile cap of FA bridges

Therefore, to restore their necessary residual life, it was drawn up a specific Maintenance Plan for the bridges on the FA Railway, with the purpose of guarantee the durability and the structural stability, especially if it is considered (a) the assets' age of approximately 50 years and their remaining life; (b) most assets have similar structural characteristics; (c) damage is identified in a significant number of assets; (d) assets were loaded by the same train compositions since 1987; (e) there is the possibility of railway operation failures due to a decrease in the bridge performance in the medium and long term. Thus, actions must be provided systematically in these assets to addres this issue.

To ensure the maintenance of the bridges in service, it was necessary to conduct a thorough evaluation of the progression of the chemical reactions demaging the concrete elements. The goal was to identify indicators that could be monitored for this purpose.

2 ASSESSMENT OF STRUCTURES AFFECTED WITH AAR AND DEF

Worldwide, the management procedures applied to many existing concrete structures affected by chemical reactions, such as AAR and DEF, includes diagnosis, serviceability, prognosis, and mitigation, [2] and [4]. Due to the typical and systematic cracks observed in FA Railway´s bridges, the presence of chemical reactions (AAR and, in some cases, simultaneously of DEF) has currently been detected, with high precision, by engineers and field inspectors, followed by an assessment (diagnosis) completed by a sampling program and petrographic examination of a limited number of cores extracted from structural elements of the bridges. In cases of structures showing evidence of chemical reactions, an integrated approach is implemented, focusing on quantifying the contribution of critical parameters. A flowchart to diagnosis and management of concrete structures affected by AAR was adopted by the concessionary. The original version of the flowchart recommended by CSA [8] was adapted to railway bridges of FA and is presented in Fig. 3.

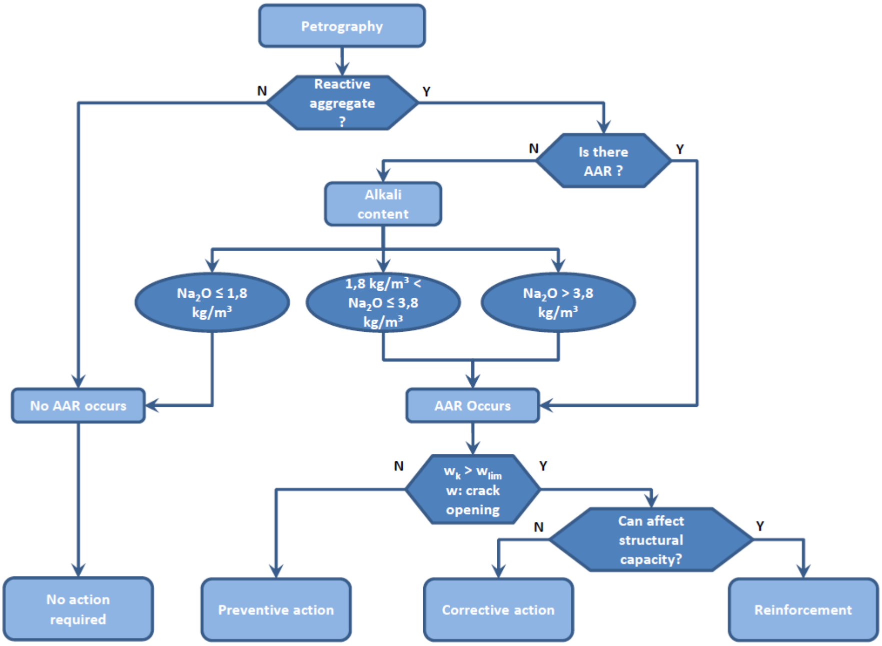

Fig. 3. Procedure proposed for the diagnosis of AAR in structures.

Recently, researchers proposed a comprehensive management tool for the diagnosis and prognosis of AAR affected structures based on a series of laboratory test procedures, [4], that can indicate the evolution of chemical expansive reactions. These tests are detailed as follows.

The Damage Rating Index (DRI) method is a semi-quantitative microscopic tool in which distinct petrographic features are counted within each 1 cm2 drawn on the surface of polished concrete samples using a stereomicroscope at 15-16× magnification. The final DRI value is normalized to a 100 cm2 area.

The Stiffness Damage Test (SDT) is a mechanical and cyclic test procedure used to assess condition of concrete affected by internal swelling reaction (ISR) mechanisms (e.g., ASR).

The Cracking Index (CI) is a proposed method for measuring the opening of cracks and their progression over time. To achieve this, the individual openings of the cracks are measured within a grid, and the total quantity of cracks is quantified.

3 THE MANAGEMENT PLAN OF THE FERROVIA DO AÇO BRIDGES.

3.1 Strategy and objectives

The strategy of the management plan for bridges on the FA Railway is to intervene annually in a greater number of damaged bridges with the challenge of seeking technically viable solutions, enabling faster and more cost-effective interventions, while mitigating risks related to structural and durability issues in these elements.

The main purpose of the maintenance is to extend the residual life of the bridges on the FA Railway, especially those where damage may compromise durability in the short to medium term. Therefore, the proposed activities will focus be on recovering structural elements where the most advanced damage has been identified.

3.2 Stability, serviceability, and durability of railway bridges affected with chemical expansive reactions.

The expansive nature of chemical reactions, such as AAR and DEF, induce in the affected concrete elements a state of stress for which they were not designed. This leads to tensile stresses that exceed the tensile strength of the concrete, resulting in the formation of mosaic-shaped cracks on their surfaces.

According to concrete international codes, a crack with openings greater than 0.4mm in reinforced concrete and 0.2mm in prestressed concrete create favorable conditions for the destruction of the passive oxide layer on steel bars, which may initiate corrosion. Therefore, when crack openings exceed thresholds, the durability of the structure is reduced.

Also, the reduction in the modulus of elasticity caused by the internal microcracking in the concrete may result in excessive deformation of the element, thereby affecting its serviceability. For example, in bridges on the FA Railway, excessive deformation of the blocks or pillars could lead to settlement in the supports, causing misalignment of the railway track.

To assess future scenarios regarding the progression of these expansive reactions and their consequences on the structure, it is essential to understand the possible failure (or rupture) mechanisms that could compromise stability. It should be noted that no references were found in the literature of structures that collapsed exclusively due to AAR. However, some cases have been reported where the expansion resulting from chemical reaction contributed significantly to the collapse. In general, interventions on structural elements are designed in such a way as to not affect their serviceability.

3.3 Criteria for prioritizing monitoring and interventions

According to the FHA [1], although many structures with AAR remain in service without interventions to mitigate or delay the effects of the reaction, failure to evaluate the symptoms or address the reaction may lead to operational issues. These include increased maintenance costs, accelerated reaction due to other mechanisms and reduced residual life of the structure.

In this way, assets will be selected for intensified monitoring and interventions, based on available data from inspections and test results, which indicate the progression of chemical reactions, level of reinforcement corrosion and the values of the concrete's elastic modulus. In the near future, the risks associated with each bridge will be integrated into the company's Bridge Maintenance System (BMS), [7].

Therefore, the aproppriate action to be taken in each case will also be defined as follows: (1) maintain inspections with the same regularity as currently, (2) intensify monitoring or (3) carry out interventions (Fig. 4).

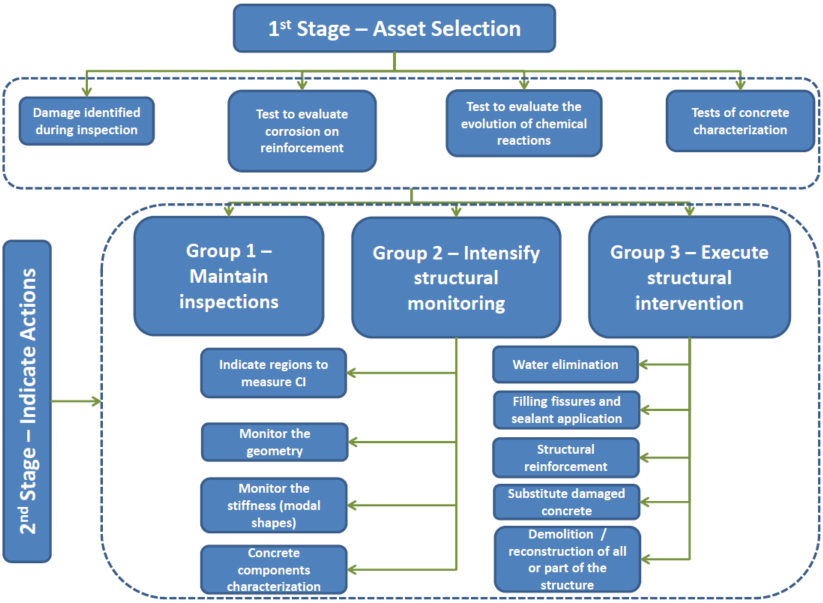

Fig. 4. Flowchart to bridge selection.

For bridges selected in Group 1, the guideline is to maintain the routine inspections in the same way as they are currently being carried out, in accordance with the frequency specified by Brazilian Standardization [3].

For structures in Group 2, monitoring techniques can be selected for specific cases. Structural monitoring may be intensified by observing the geometry of the columns and deck using topographic techniques and 3D Scanning of their elements. The structural stiffness can be monitored by dynamic tests that can be used to identify the main modal shapes of the interaction between column, pile cap and pile assemblies, with experimental determination of their effective cantilever length.

Some techniques have also been employed to monitor structures affected by chemical reactions aiming to assess the need for intervention and to aid in selecting the most appropriate treatment. It is recommended to quantify the Cracking Index (CI) and, for intervention, to perform the Stiffness Damage Test (SDT) in association with concrete expansion measures. Additionally, measuring temperature and humidity can help to define the most appropriate intervention for the asset.

Regarding Group 3, recovery techniques can be selected as interventions to mitigate the effects caused by expansive chemical reactions in concrete structural elements. These techniques have been proposed by the technical community and have demonstrated excellent results. The main interventions carried out in existing structures are: (a) elimination of water; (b) injection of cracks and application of sealant; (c) execution of structural reinforcement; (d) creation of slits and expansion joints; (e) replacement of damaged concrete; and (f) partial or complete demolition of the structure.

3.4 Intervention recommendations for structures with chemical reactions

The selection of the most appropriate intervention(s) for each bridge is based on an understanding of the progression of the chemical reaction and, therefore, the residual expansion that may still occur. Recommended interventions, categorized according with the severity of the damage, are listed in Table 2.

In general, research has classified the levels of damage to structures affected by expansive chemical reactions into five categories: negligible, marginal, moderate, high and very high, [4], as shown in Table 1. These levels are related with both the level of expansion observed and indices determined through tests such as SDI and DRI, as well as the stiffness loss resulting from the damage. Recently, ZAHEDI [5] also proposed a correlation between the expansion levels and the normalized crack indexes CI´s, which has also been used to classify the degree of damage.

Table 1. Classification of the damage degree in concrete due to ASR, [4].

Classification of ASR damage degree	Reference expansion level (%)	Stiffness loss (%)	SDI	DRI
Negligible	0.00 – 0.04	-	0.06 – 0.16	100 – 155
Marginal	0.05 ± 0.01	5 - 37	0.11 – 0.25	210 – 400
Moderate	0.12 ± 0.01	20 - 50	0.15 – 0.31	330 – 500
High	0.20 ± 0.01	35 - 60	0.19 – 0.32	500 – 765
Very high	0.30 ± 0.01	40 - 67	0.22 – 0.36	600 – 925

The reference expansion level presented in Table 1 corresponds to free expansion in concrete elements without reinforcement. To estimate the expected crack openings in reinforced structural elements, finite element models can be used, [6].

Table 2. Interventions proposed to concrete railway bridges affected by chemical reactions.

Level	Intervention	Indication
1	Water elimination	Applicable at all degrees, more suitable in cases where little residual expansion is expected, for example degrees high and very high
2	Injection of cracks and application of sealant	Applicable at all degrees
3	Execution of slits and expansion joints	Applicable in specific cases where the structural elements allow this intervention
4	Substitution of damaged concrete and reinforcement	Applicable in cases where little residual expansion is expected, for example degrees high and very high
5	Execution of structural reinforcement	Applicable at all degrees, as it allows a reinforcement gradation

3.5 Example of interventions accomplished on railway bridges

It must be emphasized that, once AAR begins in the field, there is no “universal” solution applicable to all cases; therefore, each situation should be evaluated as “unique” [10].

An interesting “physical” solution to address durability-related distress caused by AAR involves reducing water ingress and repairing damaged concrete elements. This approach was implemented on the concrete pile caps of the Soledade Viaduct, located in Congonhas, in the State of Minas Gerais. This bridge is supported by 24 columns on concrete pile caps and 2 concrete abutments. The pile caps are rectangular with variable dimensions: the smallest ranging from 6.50 meters to 11.00 meters, and the largest from 14.80 meters to 12.80 meters.

By comparing the results of NDT tests and inspections conducted in 2014 and 2018, it was concluded that there was no significant progression of the chemical reaction during this period. Therefore, to prevent the water table from coming into contact with the bottom face of the pile caps, earth moving was undertaken to fully expose the vertical faces of the pile caps, as they had been mostly filled previously. Following this, a deep drain was installed around all the blocks, effectively lowering the water table in the area. To protect slopes and other surfaces from erosion after the earth moving, hydroseeding was applied and concrete gutters were installed.

Due to the deterioration observed in the concrete pile caps, additional interventions were necessary to ensure the stability and functionality of the bridge. Initially, three centimeters of the reinforcement cover was removed from the vertical and horizontal surfaces of the pile caps, as these surfaces exhibited extensive cracking. Large cracks exceeding 1 mm, which extended into the interior of the blocks, were injected with cement grout and crystallizing additives. New reinforcements were installed, using connectors to ensure adhesion between the old and new concrete in order to prevent the residual expansive reaction process. The covering was then reconstituted by applying a layer of at least five centimeters of shotcrete, containing cement crystallization additives, to waterproof the lateral and upper surfaces. A screen was installed on the upper horizontal surface of the block to avoid shrinkage, and a slope was created to prevent water pooling.

Fig. 5. Concrete pile caps of Soledade Viaduct, before and after intervention

Another solution for durability-related distress due to AAR is the injection of cracks combined with concrete reinforcement. This method was applied to the concrete pile caps of Viaduct 074-FA, located in Coronel Xavier Chaves, in the state of Minas Gerais. This bridge is supported by 7 columns on concrete blocks and 2 concrete abutments. The pila caps are rectangular, with dimensions of 11.7meters X 6.6m X 2.5m. An interesting aspect is that the original reinforcement of the pile caps of this viaduct was installed only in its lower half. This detail was specified in the original design and later confirmed during the intervention, Fig. 6.

Fig. 6. Concrete pile caps of Viaduct 074-FA, during inspection and after cover removal

Due to the structural design of the pile cap, it was possible to measure the expansion of the non-reinforced region (composed solely of concrete) when compared to the reinforced concrete region. The average expansion measured across the four faces of the block was 0.24%, indicating a high level of damage, as shown in Table 1. Also, the crack index CI on the block faces was measured, resulting in a average CI of 4.6. These values were compared and found to align with the correlation between CI and expansion presented in [5]. Therefore, it was concluded that no further significant expansion is expected on the pile caps of Viaduct 074-FA. The chosen solution was the injection of the cracks to enhance the bridge's durability, along with installing reinforcement in the non-reinforced region of the pile cap.

4 CONCLUSION

A procedure to evaluate and manage railway concrete bridges affected by chemical reactions was adopted by the Concessionary responsible for operating Ferrovia do Aço Railway. Based on tests results and the damage identified during bridge inspections, assets can be prioritized for intensify monitoring or target interventions. This prioritization is based on the risk level of each bridge, as assessed within the Bridge Management System (BMS).

This procedure allows the concessionary company to address a greater number of damaged bridges annually, enabling faster and more cost-effective interventions while mitigating risks regarding structural and durability issues. Some of these interventions have already been executed and are presented in this paper.

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