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Non-Destructive Testing in the Strategic Research on the Performance of Bridges

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Abstract

The main purpose of bridges is to overcome physical obstacles and improve territorial mobility, therefore, knowledge of their particularities is required, such as project design, inspection and execution, maintenance service plans and others. The aim of the research is to carry out a survey of the main pathological manifestations in three reinforced concrete highway bridges (HB) – built in different years, namely: 1927, 1960 and 2018. The qualification and quantification of the anomalies were carried out and, after that, the prioritization matrix was used, which allows obtaining strategies to ensure the safeguard of the HBs. The methodology used, data collection and detailed inspection of the structure, i.e., non-destructive testing, proved to be appropriate to assess the conditions of the HBs, and also allowed to present results related to recovery services and the necessary maintenance. The pathological manifestations in older bridges are the result of project and building errors, as well as lack of maintenance service.

Keywords: Highway Bridge, Durability of Structures, Bridge Maintenance

1. Introduction

Several accidents happen on bridges and viaducts, mainly due to changes in conditions of use and lack of structural maintenance, which cause social, environmental, and economic damage. Many authors (Campos et al., 2018; Hüthwohl et al., 2018; Fowler, 2018; Alexander et al., 2017; Azenha et al., 2016; SINAENCO, 2016; Dyer, 2014; Moo, 2011) mention the following pathological manifestations as the main ones found: cracks, reinforcement corrosion, efflorescence, flaking, infiltrations, implementation failures, among others.

The bridges located in the state of Minas Gerais (Brazil) show cracks, exposed concrete reinforcement and carbonated concrete, as well as unevenness between the bridge decks due to the differential settlement of the bridge and the vegetation between pillars, among other aspects (SINAENCO, 2016). Most of these bridges were built in the early 1990s, i.e., a long time ago. Furthermore, it is important to consider the failures related to maintenance services, which allow the emergence and development of several anomalies.

In this context, many countries, including Brazil, have developed procedures for inspection, maintenance, and repair of bridges. The frequencies of their inspections vary in intervals from 3 months to 6 years, according to each country (AASHTO, 2019; Chen et al., 2021). This is what happens in the United States of America (AASHTO Manual for Bridge Element Inspection), where the standards for the inspection of bridges require that all critical elements of fracture in bridges must be inspected in periods shorter than 24 months (ALAMPALLI; PH; ASCE, 2010). This survey is carried out from the upper part of the bridge to its lower part. Notes are used to assess the state of conservation of each element. The default condition of the bridge is divided into 4 elements, namely the general descriptions: Good, Fair, Poor, and Severe. They consider factors such as the performance of the elements, deterioration rates, viable actions and preservation costs (AASHTO, 2019; Chen et al., 2021; Rafael et al., 2017; Yoseok et al., 2018; Heng et al., 2009).

In Brazil, stands out the inspection and classification processes applied to pathological manifestations in highway bridges (HBs), to consolidate a database on the conservation of these infrastructures, allowing the updating of the inspection manual developed for the Brazilian territory (Binder, 2018; Teixeira, Nogal, &

O'Connor, 2021; Rafael et al., 2017). In this maintenance manual (MTPCA, 2016), inspections in HBs are classified primarily in the conservation function of structures. They are subdivided into four different categories of activities, namely: registration activity (performed right after the work is done), routine activity (performed within a cycle not exceeding 2 years), special activities (performed within 5 years, in complex structural systems) and extraordinary activities (arising from unscheduled demands, for example, from occurrences resulting from impacts caused by vehicles). All these activities are performed only through visual analysis, except extraordinary activities.

Thus, it is important to emphasize the importance of thinking systemically about the pathological manifestations, in addition to the technical variabilities and procedures that allow analyzing and solving anomalies. With economical appropriate maintenance techniques, we can extend the useful life of bridges and reduce costs (Bukhsh et al., 2020; Wu et al., 2021). It is possible to qualitatively (performed through anamnesis and visual observation) and quantitatively (performed through the examination of materials and HBs in loco or in laboratory) identify the anomalies. Graphic representations and strategies to prioritize interventions are currently applied to enable the planning of activities based on the prioritization matrix (GUT) and/or on the SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis, and/or on the action plan, by using the 5W2H tool (Check out these questions: What? Why? Where? When? Who? How? How much?), among others that complete studies on the management of maintenance services (Braga et al., 2019; Silva Neto et al., 2021).

The purpose of this research is to carry out a survey of the main pathological manifestations, as well as to assess the current conservation scenario of three bridges, in the state of Minas Gerais, Brazil. They were built using reinforced concrete, and in different years, namely: 1927, 1960 and 2018. The inspection was based on standard procedures (DNIT, 2004; ABNT, 2019); therefore, anomalies in the HBs were qualified and quantified. The prioritization matrix was applied to enable the elaboration of strategies to guarantee the safeguarding of the bridges. The main objective of the research is to minimize inconsistencies in repair and/or conservation services, which would make it possible to propose recovery measures and extend the service life of the bridges.

2. Method

The qualitative and quantitative technical inspection was carried out based on the methods intended for the diagnosis of anomalies: visual analysis and non-destructive tests applied to HBs, namely:

i) HB-A: Rio das Velhas Bridge, 1, on Velhas River, on the town road in the city of Rio Acima (Figure 1). This bridge was built 94 years ago, with its construction started in 1923 and completed in 1927, with the following technical features: it is possible to observe a single carriageway, 104.00m in length and 5.00m in total width, with concrete and coated with asphalt. The superstructure is fragmented into sets of spans equal to 16.00m – 16.00m – 16.00m – 20.00m – 20.00m – 16.00m – 16.00m; two main stringers (1.20m in height) linked to spaced crossbeams (2.00m, in the extreme span; and 2.00 in the intermediate span). The substructure is formed by rectangular blocks supported by wooden piers – the metallic sidewalk (1.20m in width) was added after the construction (date was not informed) to be used by pedestrians.

Figure 1. (a) Side view and (b) upper view of the bridge crossing the Velhas River – HB-A

ii) HB-B: The Baronesa Bridge, on Lajes Riverside, was built in 1960, i.e., 61 years ago, and is located in the city of Santa Luzia, with the following technical features: it is 40.50 meters long and has a total width of 8.05m; of which 7.05m are made up of structural concrete, paved with asphalt, and the remaining width corresponds to a sidewalk for pedestrians (Figure 2). The superstructure is composed of sections of spans (11.475m, 15.550 m, 11.475 m, respectively) and a right/left balance equal to 1.00m. The substructure is composed of encounters at the extremities of the bridge – front wall in the encounter of reinforced concrete, side wall in the encounter of the gabion. The intermediate supports are pillars presenting a constant rectangular section: main reinforced concrete beams T or I, secondary reinforced concrete beams T or I, reinforced concrete section connected to the slab (reinforced concrete upper slab). The substructure is formed by reinforced concrete blocks – direct foundation.

Figure 2. Baronesa Bridge crossing slabs stream – HB-B

iii) HB-C: Belo Vale Bridge across the Paraopeba river. It was inaugurated in 2018, Figure 3, with the following technical features: it is 11.218m long and has a total width of 8.50m, and the usable width (m) of the road is 7.30m. The bridge is composed of structural concrete and coated with asphalt, and it has a sidewalk for pedestrians, which is made of precast concrete (1.40m in length). The substructure has encounters at the extremities of the bridge and is composed of intermediate columns of constant rectangular sections, precast columns, and transverse reinforced concrete linked to solid panel slabs. The substructure is formed by rectangular crown blocks supported by root piles.

Figure 3. Belo Vale Bridge crossing Paraopeba River – HB-C

In summary, the bridges subject to analysis in this research are 94, 61 and 3 years old. They were selected due to the ease of access to their registration information, which is made available by a public agency, as well as to information about their building techniques. The characteristics of the bridges are shown in Table 1.

Table 1. Characteristics of the Highway Bridges (HB)

HB	Brazilian Standard	Num. vehicles	Population	CO_2 Emission in 2019 (tCO_2)
A	-	4.738	10.420	4.160.083
B	NB1	87.943	220.444	
C	NBR7188	4.216	7.719	

Source: ABNT, 1960; ABNT, 2013; IBGE, 2021 (a-f); PBH, 2021.

The studies followed the inspection procedures described below:

a) Registration analysis: projects (structural, building process, among others), environmental and operational conditions and maintenance services in HBs.

b) Preliminary analysis: visual observation to identify all components of the HBs.

c) Visual inspection (MTPCA, 2016): the structural conditions and iconographic survey of all regions of each bridge were classified using a Nikon Coopix P600 camera, with zoom of 60x adjustable to 120x, and Dynamic Fine Zoom – this lens covers a range between 24-1440 mm and has a Super ED (Extra-Low Dispersion) glass to improve the quality of the image.

e) Non-destructive tests: hardness test carried out with an equipment model Silver Schmidt Type SH01-003-0374 (Figure 4). During the test, we were aware that the results could be subject to interference resulting from several factors, such as humidity (in wet weather, the saturated structure presents a strength that can be up to 20% lower), so it was decided to evaluate them in the driest period (in each location), i.e., with relative humidity equal to 60.13%, 80.27% and 66.08% for the bridges HB-A, HB-B and HB-C, respectively. The carbonation test DIN (2007) was carried out on the foundation blocks and beams. The test started with the removal of a portion of the concrete (approximately 50 mm), performed by a cut orthogonal to the position of the reinforcement. The broken surface was cleaned with a brush and the pH indicator based on 1% phenolphthalein in 1000ml of alcoholic solution was sprayed. The carbonation depth was measured using a 0.01 mm precision caliper (Figure 4).

Figure 4. Hardness and carbonation test

f) Concrete microstructure analyses: using the Jeol jsmit 300 Scanning Electron Microscope (SEM) operating in high vacuum. It was coupled to an Oxford energy spectrometer (EDS) without liquid nitrogen. The samples of the pillars, beams and foundation blocks of the three bridges were cut into 1cm cubes. They were metallized with gold (195 Ä layer) and with carbon (195 Ä layer), according to a better analysis of the interface area between the aggregate and the paste (because of carbonation). The SEM images were obtained in secondary electrons in the voltage range between 10 Kv and 20 Kv, and, for EDS, in the voltage of 20 Kv.

g) The prioritization intervention regarding the strategies to solve pathological manifestations is essential and consists of a hard-working procedure. There is a possibility of using the prioritization matrix tool in the planning for the conservation and repair, i.e., the GUT prioritization matrix identifies problems through 3 criteria: Gravity, Urgency and Tendency, and is widely used in the business sector to assist in the definition of priorities and decision-making. Gravity is defined as the intensity, the depth of the damage that the problem may cause if there is no intervention on it, the urgency refers to the time for the results to be undesirable if there is no intervention and, finally, the tendency is the development that the problem will have in the absence of action. Therefore, the calculation of GUT (= G x U x T) indicates the highest or lowest priority for a given demand (Braga et al., 2019; Silva Neto et al., 2021), see Table 2.

h) Estimated life cycle: analyzing the repair and conservation services and boundary conditions that result from errors in the quality of the project and/or in the choice of material, as well as the environmental conditions, i. e., the durability and life cycle of the bridges, it is possible to estimate the durability of concrete structures, as shown in Equation 1 (Barbosa; Rosse; Laurindo, 2021):

$$LC_{Estimado} = LC_R \,.\, X.\, Y.\, Z \quad (1)$$

where: $LC_{ESTIMATED}$ the estimated life cycle of the bridge;

LC_R is the minimum life cycle, which is usually prescribed in the standardization, i.e., 50 years with regard to the NBR 15575 (Residential Buildings - Performance Part 1: General Requirements, 2021);

X, Y, Z are the indicators given in Table 3.

Table 2. GUT scoring method applied to pathological manifestations and degradation of lifespan

Amount	Gravity	Urgency	Tendency
	Result	Deadline	Progress
5	Highly serious	Highly urgent	Highly full
4	Very serious	Very urgent	Very full
3	Serious	Urgent	Full
2	Little serious	Little urgent	Little full
1	Not serious	Not urgent	Not full

Source: Adapted from Barbosa, Rosse, & Laurindo, 2021.

Table 3. The watertightness indicators of the bridges for the characteristics of quality and environment

Indicators		Terms of use		
		BAD	ORDINARY	GOOD
X	PROJECT: building details	0.8	1.0	1.2
Y	COATING MATERIALS: waterproofing	0.8	1.0	1.2
Z	ENVIRONMENTAL: aggressive agents (include CO_2)	0.8	1.0	1.2

Source: Adapted from Barbosa, Rosse, & Laurindo, 2021.

The purpose is to insert the concept of the GUT matrix in the life cycle, and thus better understand the effect of the anomalies. This procedure will allow evaluating the effect of the current state of conservation of the HBs.

3. Results

3.1 Watertightness Problems

Transverse joints are intended to transfer the vertical and horizontal load from the vehicles to the beams, which can adapt to the displacements of the bridges (Ma et al., 2020). HB A and B showed a lack of such joints, Figures 5 and 6, and this compromises the structural system, as well as compromises their life cycle, since it favors the development of cracks and allows the infiltration of residues and other hazardous agents (Shi et al., 2019; Allard et al., 2018; Karthik et al., 2016). HB – C showed a good state of conservation. It is important to consider that inefficient joints and encounters facilitated the appearance of cracks that allow the percolation of water through concrete structure (Figures 6 and 7).

Figure 5. Expansion joint: lack of expansion joint in (A) HB-A and (B) HB-B; and the presence of expansion joint in (C) HB-C

Thus, in the river's border/HB, it was possible to observe the rupture, in HB–A and HB-B (Figure 7), in the concrete next to the metallic support of the sidewalk, displacements, cracks in the beam supporting the sidewalk and failures in the concreting on the slab. These cracks occurred mainly in the rainy season due to drainage failures, which led to leaching of the concrete and, consequently, to efflorescence, Figure 7 (Zhang et al., 2020; Xue et al., 2018; Huthwohl et al., 2019).

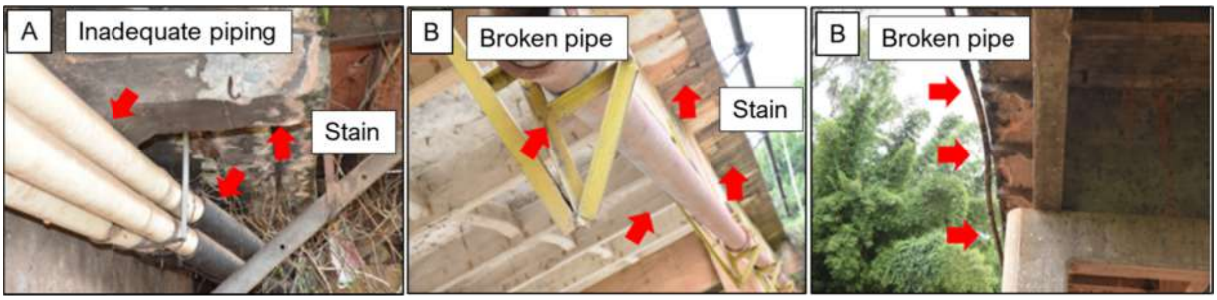

Figure 6. Drainage system: (a) HB-A; (b) HB-B

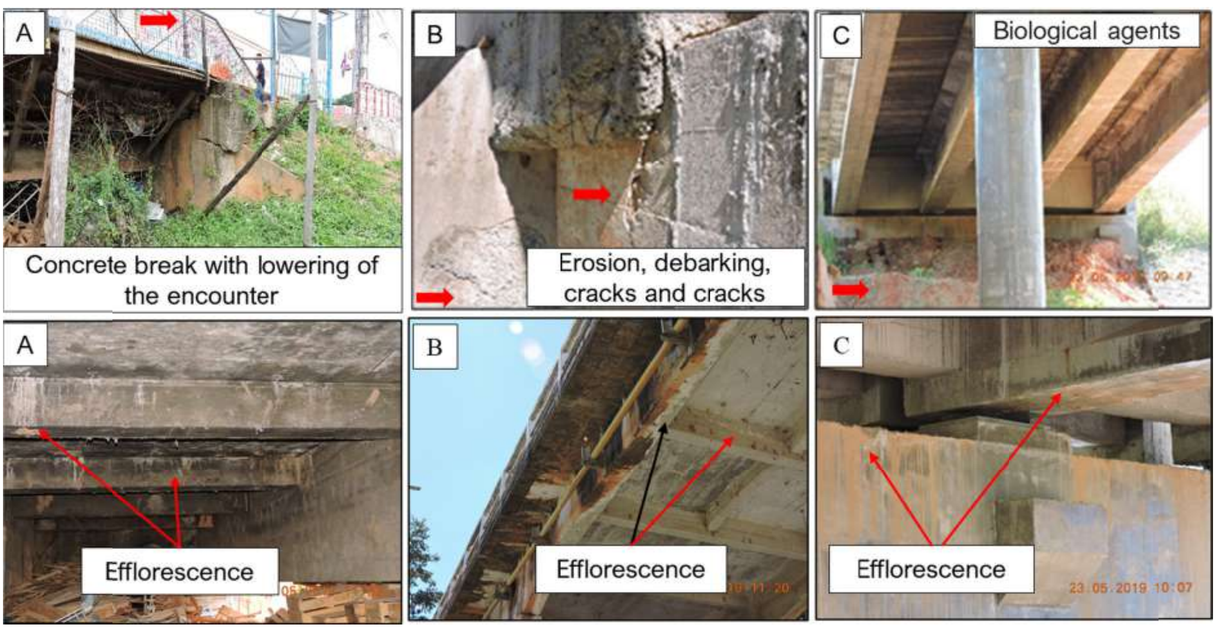

Figure 7. Efflorescence HB A, B and C

3.2 Structural Design, Execution and Maintenance Problems

The following were found in the concrete structure: honeycombs, exposed reinforcement, corrosion of the reinforcement, cracks, patches in the concrete, insufficient cover (Figure 8, Tables 4 and 5). Carbonation tests were carried out on structural elements (beams and pier) and on infrastructure elements (foundation blocks) (Figure 9).

Table 4. Carbonation test results – identifying the degree of carbonation

HBs	A	B	C
Column	XX	XX	X
Beam	XXX	X	X
Foundation beam	XXX	XX	XX
Foundation blocks	XXX	XXX	XX

Note. X (little condition); XX (mean condition); XXX (high condition).

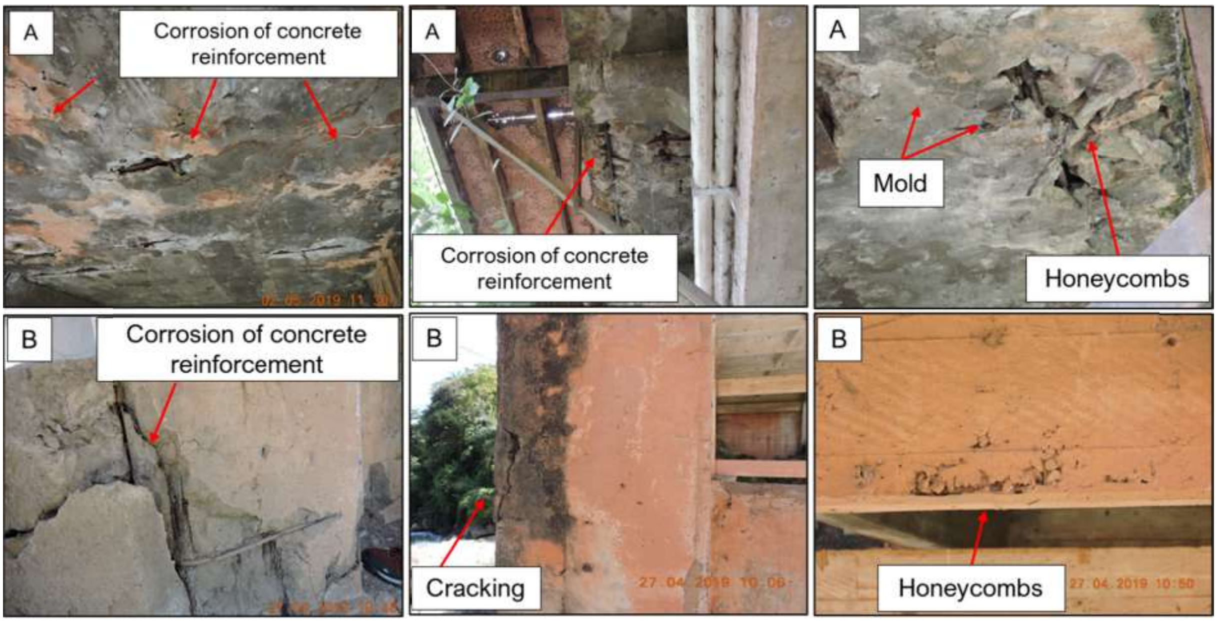

Figure 8. Pathological manifestation

Table 1. Reinforcement coating thickness

HBs	A	B	C
Column	-	XX	-
Beam	XXX	XXX	X
Slab	XXX	-	-

Note. - (excellent); X (good); XX (mean); XXX (poor).

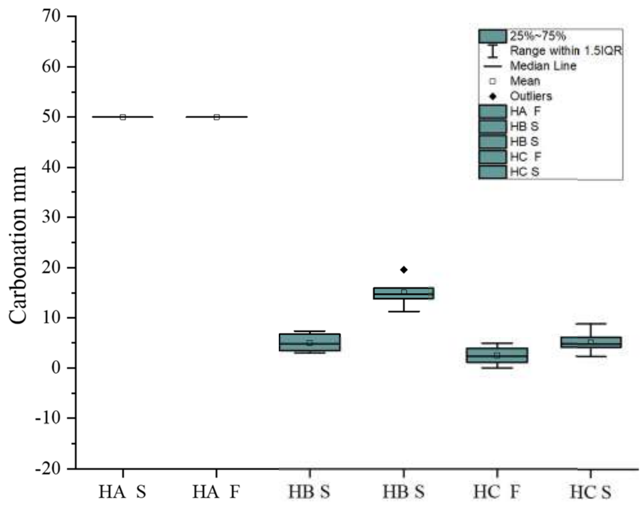

Figure 9. Carbonation index

The HB-A is the oldest of the three and the results concerning it were as expected. There is high carbonation in a significant cover thickness (50 mm). However, there is no carbonation in the foundation block (HA F) or in the central column (HA S), but they presented cracks resulting from being in a low region (inside the river or submerged). Regarding the HB-B, the beam shows an average of 4.94 mm of carbonated depth and, for the foundation block, the depth value is 15.07 mm. The beam is not located near the river and did not present any cracks, but it is influenced by the variation of the river level, i.e., the wetting and drying cycle. The HB-C is the most recent of the three bridges analyzed, and in which the foundation block shows an average of 2.46 mm of carbonated depth, while, as regards the connection beam of the block, this value is 5.15 mm.

Figure 10 shows the hardness values of the concretes of the three bridges. The hardness of the concrete for the HB-A is 51.4 and 61.2 MPa, regarding the foundation block (HA F) and the pier (HA S), respectively; as for bridge “B”, the beam (HB S) presented an average of 61.1 MP and the pier (HB F) presented 58.6 MPa (HB F), regarding the hardness of the concrete; as for bridge “C”, the foundation block (HC F) presented an average hardness of 43.1MPa, and the beam (HC S) 32.0 MPa.

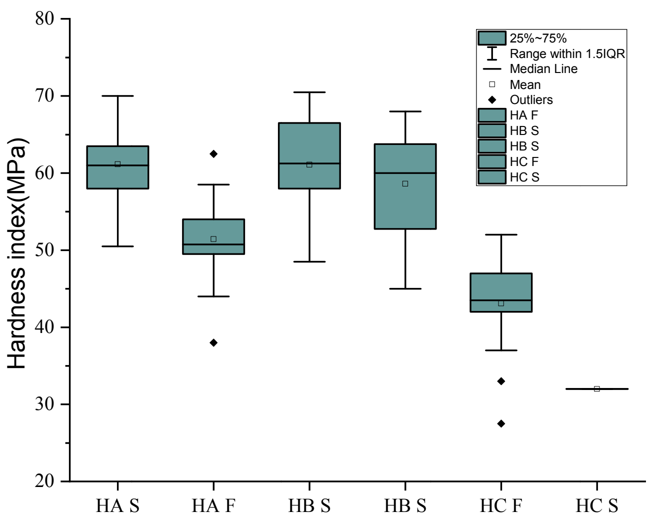

Figure 10. Hardness index

As can be seen in Figure 11, foundation blocks (and, in this case, in the three HBs assessed) were detached from the soil and exposed the piers to the environment. Moreover, there was a reduction in the structural section caused by floods and erosion, chemical agents aggressive to the concrete and lack of maintenance services, among others (Skrzypczak, Słowik, & Buda-Ozóg, 2017; Gega & Bozo, 2017).

Figure 11. Pathological manifestations – HB-A

3.3 Safety in the Use and Operation of HBs

The permanent signage (road safety signs) is part of a fixed traffic control system designed to order traffic jams, and to alert and guide users (DNIT, 2010). HB-A has a traffic light at each of its extremities because there is only one lane for both directions of traffic; however, there were no signposts to signal their presence, as shown in Figure 12, also, it is necessary to carry out maintenance services on the road marking signs, due to wear. HB-B does not have a sidewalk for pedestrians, so it is necessary to include a signpost pointing out the direction, i.e., "pedestrian, walk on the right/left", as well as there is the need to delimit the lane (regulating the opposite-flow directions). HB-C is well signposted, it has the mandatory signposts; however, it needs a sign indicating that it is forbidden to overtake – this procedure is mandatory on bridges. Table 6 presents a summary of the survey on the items that ensure the safety of users and pedestrians.

The asphalt pavement, Figure 13, needs maintenance/conservation services on HBs A and B, since there were several points of wear and tear, holes, transversal and longitudinal cracks, "alligator cracking" and unevenness throughout the road over the bridge.

Figure 12. Traffic signs and road marking lines on bridges A, B and C

Table 2. Types of mandatory safety signage on bridges

Mandatory signage	HB		
Signposts	A	B	C
Bridge identification	-	-	-
Narrow bridge	-	-	X
Forbidden to overtake	-	-	-
Total length of the bridge	-	-	-
Horizontal signage	A	B	C
Painting of the partition tracks	-	XXX	-
Painting of the boundary strips	X	XXX	-

Note. XXX (outspread), XX (some points), X (few points) and – (unidentified).

Source: Rashidi, Lemass, 2011.

Figure 13. Pathological manifestations on the asphalt pavement (a) HB-A; (b) HB-B

Side safety devices (SSD) must be strong enough to prevent a vehicle from falling off the bridge and to properly guide the vehicle back into its correct lane on the road, without causing any damage to another safety device. The standards set for side protections on road bridges are divided into four different moments: bridges projected up to 1960, from 1960 to 1975, from 1975 to 1985; and bridges projected after 1985 (Side Safety Devices: Wheel Guards, Guard Rails and Barriers - Service Specification., 2006). Figure 14 and Table 7 show the conditions of the parapets.

As in the case of the SSD, the condition of the sidewalk also needed attention, as shown in Figure 14. HB-A underwent an implementation of a metallic sidewalk for pedestrians (1.20m wide) after its construction; however, it presents signs of corrosion and deterioration throughout the entire bridge, as well as concrete rupture. HB-B does not have a sidewalk for pedestrians or cyclists. These anomalies derive from the exposure to environmental agents, such as humidity and carbon dioxide emissions, which corrode and deteriorate the material. All these issues are maximized by lack of maintenance (Rivera-Corral et al., 2017).

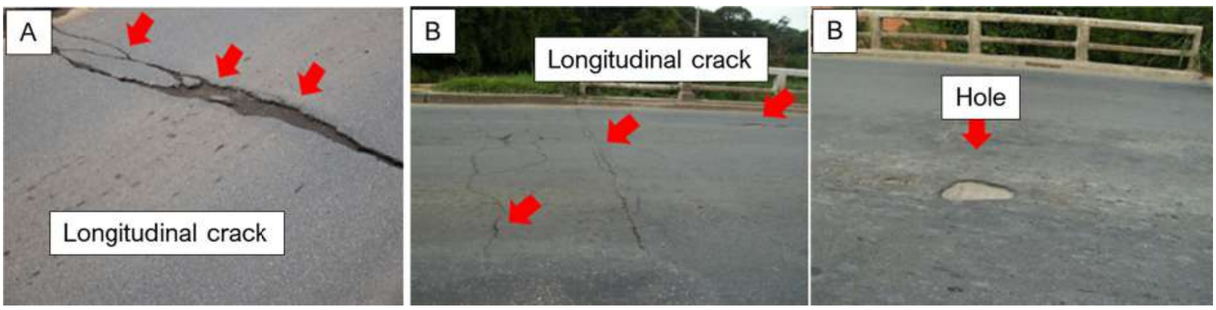

Figure 14. SSD Parapet on HBs (a) A, (b) B and (c) C

Table 7. Anomalies observed in the parapets

Pathological manifestations	HB -A	HB -B	HB - C
Cracks	XXX	XX	-
Slit	XX	XXX	-
Broken concrete	XX	XXX	-
Exposed armor	X	X	-
Concrete voids	-	XX	-
Oxidation	XX	-	-
Corrosion	-	X	-

Note. XXX (outspread), XX (some points), X (few points) and – (unidentified).

4. Analysis

4.1 Reinforced Concrete Structures

The lack of suitable: database, design, building and maintenance of the HBs, drip pans and drainage systems (Figures 5 and 6) generated leaching of the composite concrete and, consequently, efflorescence (Figure 7), due to the combination of leaching and carbonation processes (Hüthwohl, Lu, & Brilakis, 2019; Sañudo et al., 2019). These anomalies occurred due to the deterioration of the material, concrete batching or production mistakes, execution mistakes, poorly designed paving and earthworks project, overload, high traffic volume, inadequate drainage system and lack of life cycle (Gómez-Meijide et al., 2018).

The deterioration of the concrete (Yang & Frangopol, 2020) on the HB-A, which can decrease the mechanical properties of the concrete, causes structural damage, as well as compromises its durability and the total safety of the structure (Phillipson, Emmanuel, & Baker, 2016; Agred, Klysz, & Balayssac, 2018; Blanco et al., 2019). There are several factors, all identified in the studied HB, capable of causing such anomaly, for example, cracks, slits and carbonation, among others (Agred, Klysz, & Balayssac, 2018). The mechanical properties of concrete are influenced by age, curing (especially the effect of concrete saturation) and carbonation, as seen in the results regarding the hardness tests (Figure 10). The average strength of concrete is influenced by the carbonation depth (Šavija & Luković, 2016).

Analyzing Figure 9 and Table 4, it can be seen that the HB-A, built in 1927, shows a high carbonation index, the decks and stringers presented exposed reinforcement (Figures 5, 6, 7 and 8) and concrete flaking (Figures 5, 6, 7 and 8) due to corrosion products. Since 2003, the Brazilian standard defines a coating thickness for reinforced concrete dependent on the correlation with the environmental aggressiveness, whereas, before that year, 20 mm was the measure adopted for all concrete structures. HB-B is located in an urban region characterized by heavy traffic; it shows a high carbonation level, Table 5, and the corrosion of the reinforcement was evidenced through the columns of the bridge. HB-C, the most recent (3 years old), shows few defects and complies with the requirements of the current Brazilian standard, however, it is very important to have preventive maintenance services (ABNT, 2019).

With respect to reinforcement corrosion, it is important to point out the increase in CO_2 rates caused by the greenhouse effect, which tends to negatively change environmental aggressiveness, and the faulty concrete production stages, which can result in voids, (Peng & Stewart, 2016). Several points of steel corrosion were found on HB-A and HB-B, in the following elements: piers, beams and slabs, which are critical and can lead to the collapse of the structure if the repairs are not carried out. Therefore, HB-A is closed for lack of security.

In the foundation block facing the city of Nova Lima, the wooden piers are fully exposed, and some of them present an advanced stage of decay and considerable section loss. Regarding the HB-B and HB-C, the beam close to the encounters has deteriorated due to contact with water. The deterioration was hard due to the rainy season in the region (rainfall season), Figure 11. In the case of the HB-A, wooden piers were used, although the use of this material in the foundations of special structural buildings is not recommended, due to several restrictions, nevertheless, it would be an appropriate alternative in 1927 (Bettiol et al., 2016). Figure 6 depicts the non-compliance of these foundations, which are exposed to environmental degradation processes (caused by microorganisms) that compromise the strength and lifespan of the columns.

4.2 Microstructural Analysis of Concrete

In the SEM images, it is possible to visualize the concrete matrix and some particles from the aggregates coming from the concrete of the three HBs. Through Figure 15, it is possible to observe a sample of the pillar of HB- A, in which several particles of quartz sand can be seen, which is confirmed by the EDS analysis (Figure 16), as well as some pores present in the concrete matrix.

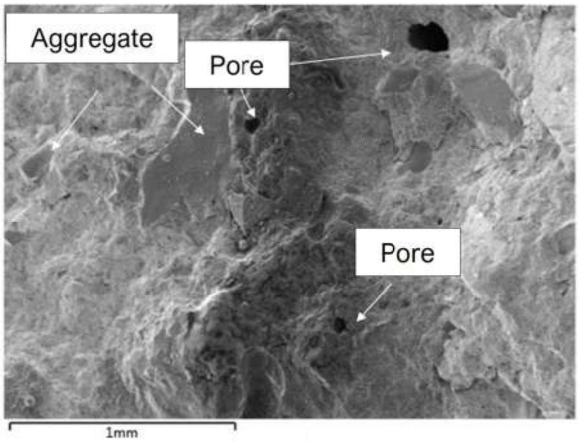

Figure 15. HB-A, central pillar map, 50x

The presence of C-S-H (Figure 17) was found in the entire sample HB-A, visualized as clumps of particles, small equiaxed grains forming flakes. This predominant morphology is characterized as being of type III (Lea, 1971; Barnes & Bensted, 1983). It was also detected the presence of crystals of calcium hydroxide, Portlandite (CH), which is another product of C3S and C2S hydration.

This presence of CH corresponds to the alkaline reserve that guarantees the passivity of the reinforcement contained in the concrete matrix (Figures 18 and 19). It is characterized by thin and elongated hexagonal plates (Neville, 2018), often only a few tens of micrometers wide (Harutyunyan et al., 2003), and clearly defined edges, usually arranged in large clusters around the aggregate (Diamond, 2004). A similar behavior was observed in the sample HB-B, where the presence of CSH bound to the aggregate was also identified.

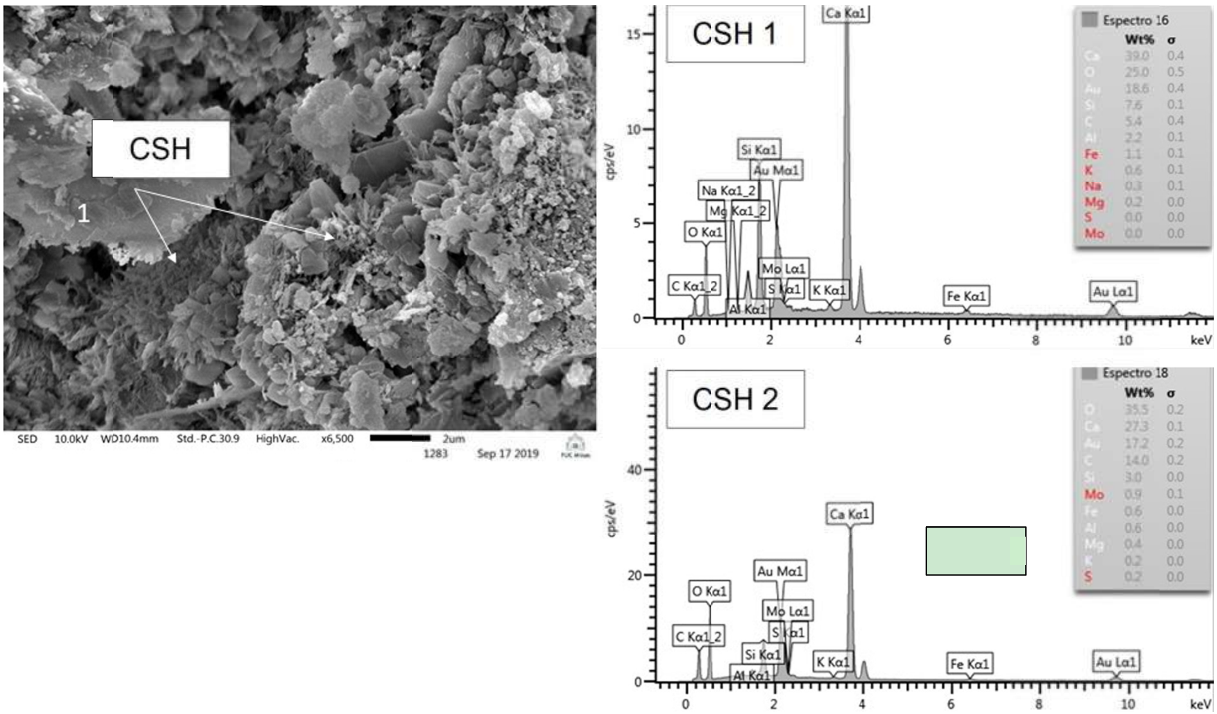

Figure 16. In the mortar work, at a magnification of 2000x, EDS - Calcium hydroxide and mortar and CSH

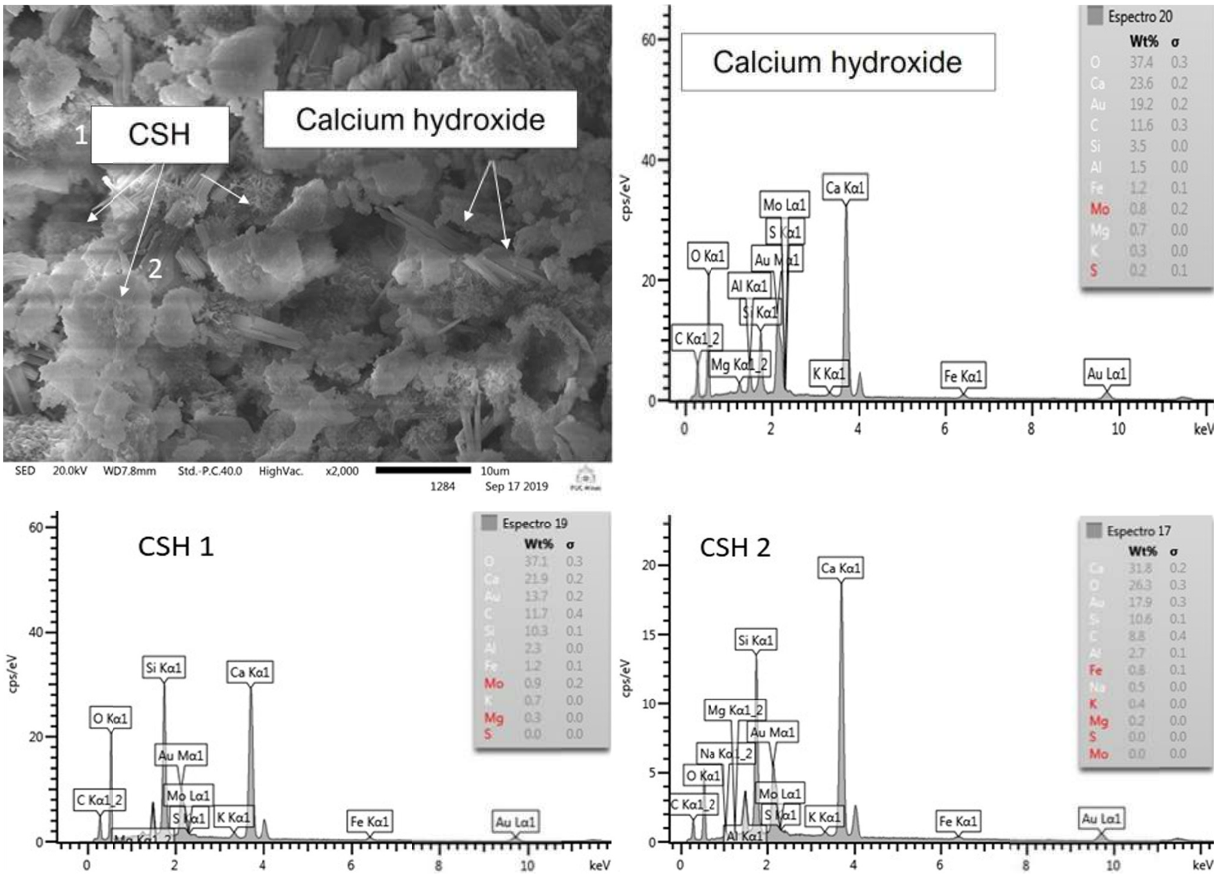

Figure 17. In work A, mortar, 6500x, EDS - Calcium hydroxide

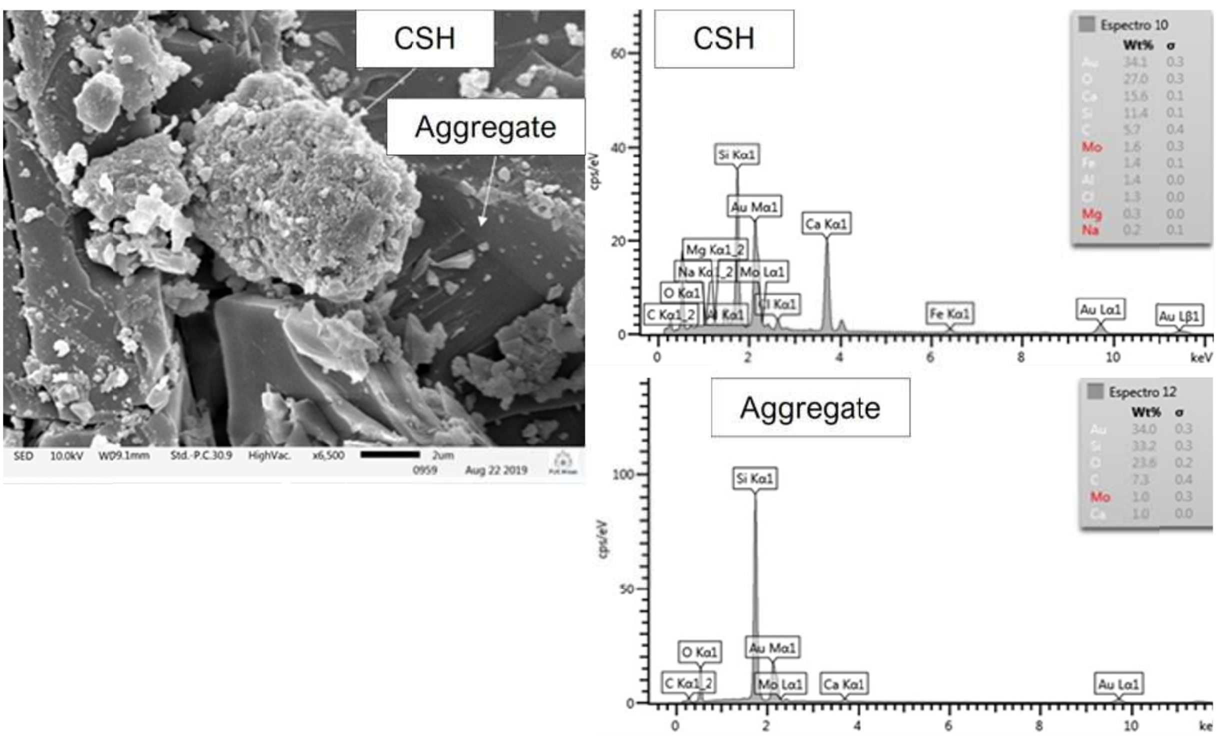

Figure 18. In work B, Pillar, Mortar, 6500x - EDS CSH and Aggregate

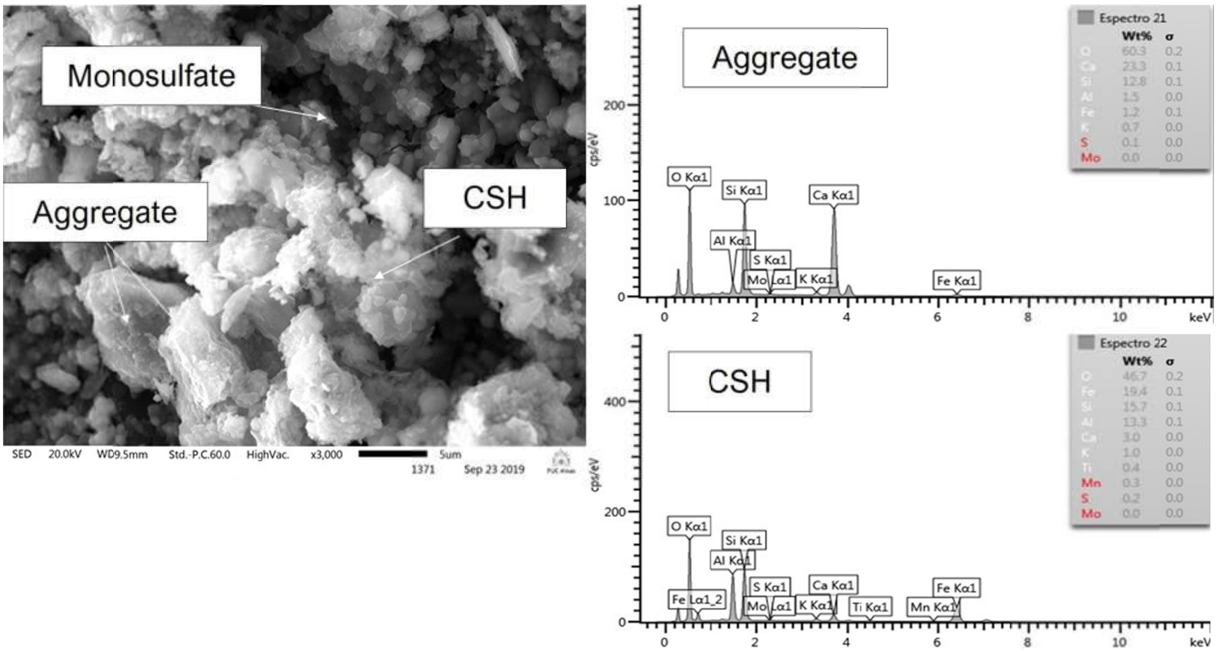

Figure 19. In work C, Beam, 3000x - EDS Quartz and CSH

Regarding the sample HB-C (Figure 20) it was found a structure formed by rounded hydrated products, in the form of flakes, whose microanalysis indicated that some of them were hydrated calcium silicates, C-S-H and the others were unstable ettringite that was turning into monosulfate (MS) (Lea, 1971; Barnes & Bensted, 1983).

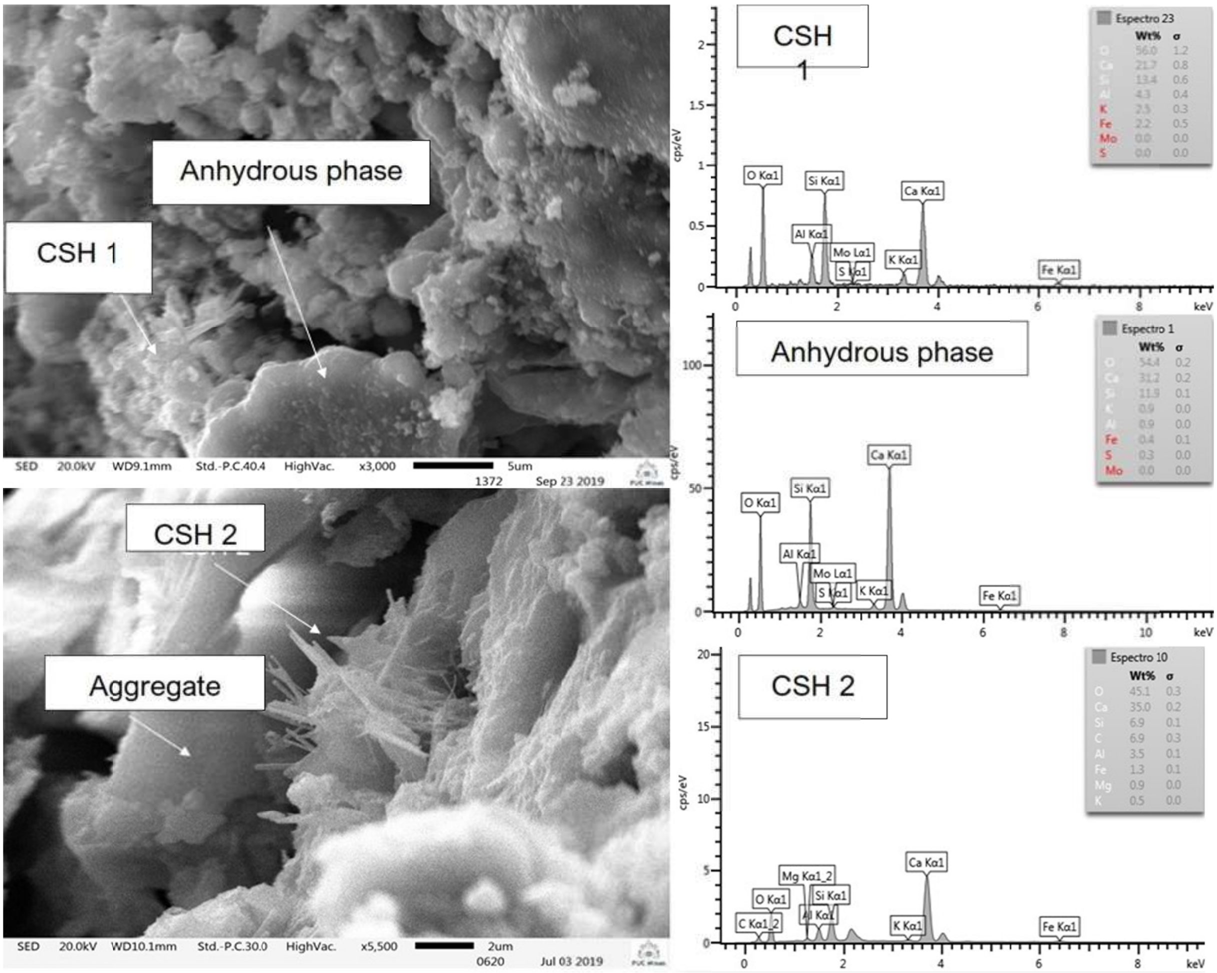

Figure 20. In HB-C, Beam under 3000x magnification, identifying the Anhydrous Phase; and microscopy of the foundation block, aggregates under 5500x magnification – EDS CSH and anhydrous phase

In another micrograph of the sample HB-C (Figure 19), a grain of anhydrous cement was found, along with a C-S-H phase present in most of the sample (3000x magnification). Through the 5500x magnification, it is possible to identify the formation of C-S-H close to the aggregate that is present in the sample.

4.3 Prioritization Matrix

There are several anomalies in the structures of the three bridges, which compromise durability and security, such as, for example, reinforcement corrosion, sulfate attacks, traffic volume, humidity, cracks, joint errors, overload, biological agents, drainage errors, erosion, efflorescence and concrete voids, which are presented in Table 8 and Figure 21 and Figure 22. Therefore, the GUT prioritization matrix helps in making decisions, i.e., the GUT calculation (= G x U x T) points out the highest or lowest priority for a given demand, It was possible to observe that the adopted procedure allowed the elaboration of an intervention schedule based on the anomalies in the HBs, as well as made it possible to predict a possible anomaly based on the gathered data, for example, the corrosion of the reinforcement (or the steel bars) observed in HBs A and B, which allowed to foresee the need for preventive maintenance to minimize it in HB-C.

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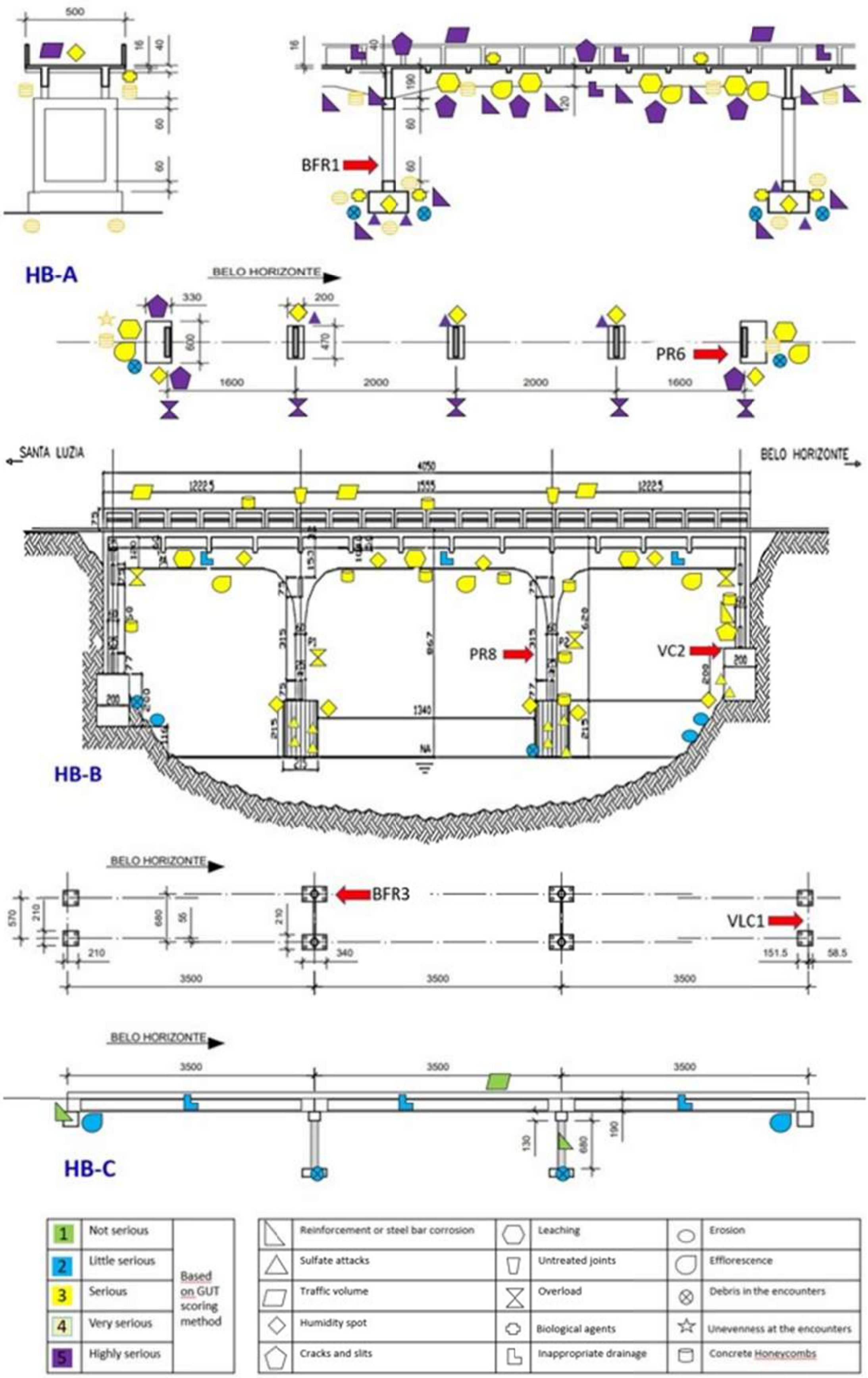

Figure 21. Main pathological manifestations observed in the HBs

Table 8. GUT of the main pathological manifestations identified in the HBs

SWAs	A				B				C			
Prioritization	G	U	T	Score	G	U	T	Score	G	U	T	Score
Reinforcement Corrosion	4	5	5	100	3	4	3	36	1	1	1	1
Sulfate attacks	4	5	5	100	4	3	3	36	-	-	-	0
Traffic volume	5	5	5	125	3	3	4	36	1	1	1	1
Humidity spot	3	2	5	30	3	3	3	27	-	-	-	0
Cracks and slits	4	4	5	80	3	3	3	27	-	-	-	0
Leaching	3	3	3	27	3	3	3	27	-	-	-	0
Untreated joints	-	-	-	-	3	3	3	27	-	-	-	0
Overload	5	5	5	125	3	3	3	27	-	-	-	0
Biological agents	3	3	3	27	-	-	-	0	-	-	-	0
Inappropriate Drainage	4	5	5	100	3	2	2	12	2	1	2	4
Erosion	3	4	5	60	3	2	2	12	-	-	-	0
Efflorescence	3	3	3	27	3	3	3	27	2	2	2	8
Debris in the encounters	2	2	3	12	3	2	2	12	2	2	2	8
Unevenness in the encounters	3	4	4	48	-	-	-	0	-	-	-	0
Concrete voids	4	4	4	64	3	3	3	27	-	-	-	0

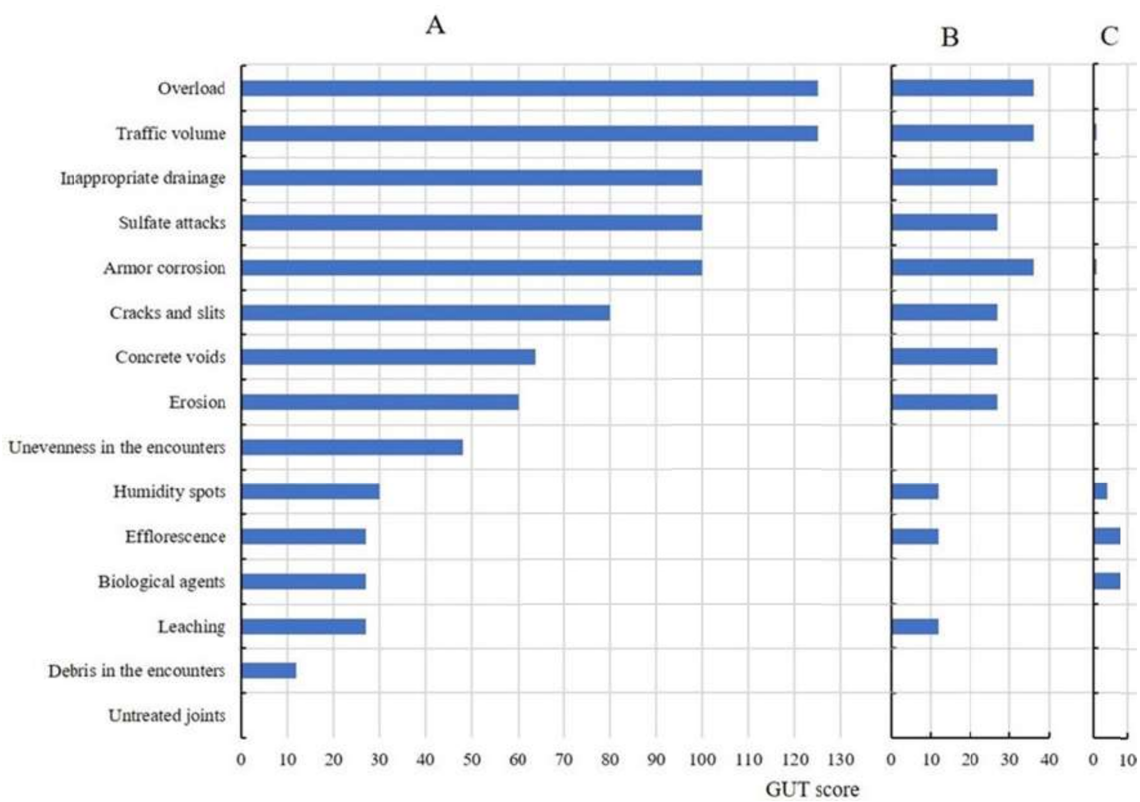

Figure 22. GUT results recorded for HB-A, HB-B and HB-C.

HB-A showed a high number of issues related to anomalies, which means a great urgency for an intervention. In addition, it was possible to order the priorities regarding the pathological manifestations, namely: Traffic volume – Excessive load – Reinforcement corrosion – Sulfate attacks – Inappropriate drainage – Cracks and slits – Concrete voids – Erosion – Unevenness in the encounters – Humidity spots – Leaching – Biological agents – Efflorescence – Debris in the encounters – Untreated joints.

HB-B presents lower intensity than HB-A. The main issues seemed to be the same, and it evidenced that the 40-year difference between the bridges was not enough to justify adjustments in the projects, specifications and execution aimed at preventing the emergence and proliferation of these pathological manifestations. The priorities regarding HB-B can be ordered as follows: Reinforcement corrosion – Traffic volume – Excessive load – Sulfate attacks – Inappropriate drainage – Erosion – Concrete voids – Cracks and slits – Leaching – Efflorescence – Humidity spots. However, the interdependence between the anomalies (Figure 23) must be taken into account to define the ordering of activities. Thus, all that it needs is to have its issues solved, namely: Biological agents – Efflorescence – Humidity spots – Reinforcement corrosion – Traffic volume (Figure 23).

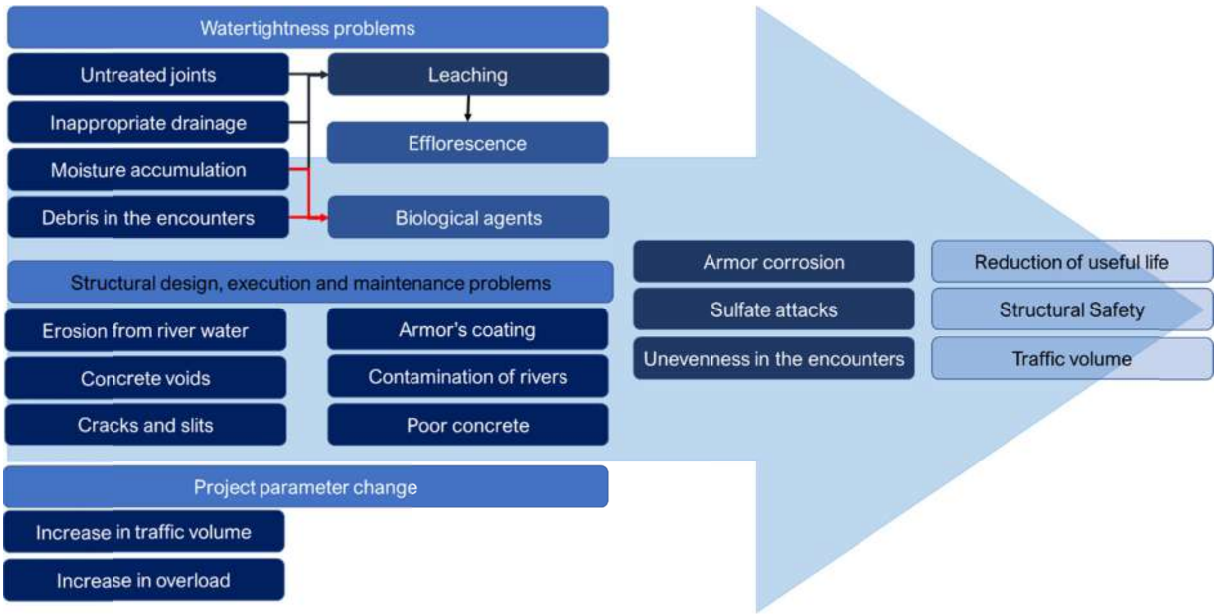

Figure 23. Systemic map of pathological manifestations found in HBs

HB-C presented 5 (five) pathological manifestations, with a record that ranges from low to insignificant gravity, urgency and trend. It is possible to highlight the three issues that register the same priority limit, as they are correlated manifestations: humidity causes leaching, which, in turn, causes efflorescence and humidity associated with locations subject to poor insolation (beneficial for the proliferation of microorganisms).

There are no description projects related to the HBs, i.e., details of building techniques, specification of the concrete, type of reinforcement, maintenance service manual. Therefore, this research can assist in terms of current and future repairs, since HB-A was closed because it has many anomalies (reinforcement with high corrosion, for example) that compromise safety (whether structural or of the users). In 2010, the HB-B was subjected to a maintenance service that is not registered with an official department (DNITT); there was only a simple technical report, hence, preventive and corrective maintenance are required to ensure its safety and life cycle.

The HB-C shows some flaws and anomalies, which already require maintenance and follow-up to ensure its durability. Therefore, the need to update HBs A and B is evident, as these are important structural reinforcements to increase the load capacity to meet regional demand, and to rectify and/or improve drainage, waterproofing and signage security, among others. All HBs need a use, operation and maintenance manual that is carefully elaborated and includes maintenance and inspection procedures and schedules. If necessary, future interventions must be set to ensure the ability of the HBs to operate properly (Silva Neto et al., 2021).

In the calculation of the estimated life cycle (Equation 1), the minimum value estimated by the Brazilian standard (50 years) was adopted, which can be replaced by the current standard in the country under study. Table 9 shows the estimated service life in relation to the design parameters, coating materials and environmental issues, and it can be observed that there was a reduction to almost half when considering HB-A and to 36.00% when considering HB-B. The life cycle damage is expressive and demonstrates that these items are very important to measure the service life of the construction.

Table 9. The estimated life cycle of the bridge.

Indicators		HB A	HB B	HB C
A	Project	0.8	1.0	1.0
B	Coating Materials	0.8	0.8	1.0
C	Environmental	0.8	0.8	1.0
$LC_{Estimado} = 50 . A. B. C$ (Years)		25.6	32	50
Degradation - D_l (Weighted Average)		0.47	0.68	0.97
$LC_{Estimado} = 50 . A. B. C . D_l$ (Years)		12.0	21.9	48.3

5. Conclusions

If we consider the progress of urbanization in cities, it is easy to observe the need for improvements in the infrastructure of the highway bridges (HBs), which, in turn, need inspection and maintenance services throughout their life cycle. This inspection must encompass technical activities ranging from data collection (project and building), detailed structural inspection and reporting, to the evaluation of the state of the work and recommendations. The procedure introduced in this study enables the management of maintenance services to ensure better performance and a longer life cycle, in addition to influencing economy and functionality factors. Therefore, this methodology was appropriate to lead to results capable of supporting the identification of defects and the quantitative measurement of recovery and maintenance services.

The main pathological manifestations were associated with the corrosion of steel bars due to project flaws, coating specifications and execution, exposed bars, concreting nests, overload caused by high traffic volume, and problems in the drainage system – which led to several anomalies associated with humidity. Accordingly, and based on the evaluation process, it was possible to observe the need to recover bridges A and B, based on structural reinforcements to improve the load capacity and meet regional demand, and the need to install adequate and updated safety, drainage and waterproofing systems. Besides, all HBs require a carefully elaborated use, operation and maintenance manual including maintenance and inspection procedures and schedule. If necessary, future interventions must be set to ensure the capacity of the HBs to operate.

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