applied sciences

MDPI

Article

The Use of De-Icing Salts in Post-Tensioned Concrete Slabs and Their Effects on the Life of the Structure

Tomás Luis Ripa Alonso [1,2], Noemí Corral Moraleda [2], Marcos García Alberti [1,*], Rubén Muñoz Pavón [1] and Jaime C. Gálvez [1]

[1] Departamento de Ingeniería Civil: Construcción, E.T.S. de Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid, 28040 Madrid, Spain; tomasluis.ripa@upm.es (T.L.R.A.); ruben.mpavon@upm.es (R.M.P.); jaime.galvez@upm.es (J.C.G.)
[2] LRA Infrastructures Consulting, Avda. Concha Espina, 28016 Madrid, Spain; noemicorral@lraingenieria.es
* Correspondence: marcos.garcia@upm.es; Tel.: +34-91-0674121

Abstract: This article expounds on the problem of the use of de-icing salts in the corrosion of steel rebars in bridge decks and their effect on post-tensioning elements. In particular, this paper focuses this problem on structures affected by an aggregate–alkali reaction and without any waterproof treatment using the example of one structure whose repair was carried out in 2020. In this structure, the internal stresses due to the aggregate–alkali reaction caused longitudinal cracks in the upper face of the deck, through which the penetration of chloride ions was concentrated, causing, finally, the brittle fracture of the steel bars and the corrosion of the prestressing elements. This article also explains some conclusions about the most probable mechanisms that resulted in the brittle fracture of the steel bars due to the extraordinary and unexpected nature of this phenomenon.

Keywords: de-icing salts; post-tensioned concrete slabs; corrosion fatigue; cracking; durability

check for updates

Citation: Ripa Alonso, T.L.; Corral Moraleda, N.; García Alberti, M.; Pavón, R.M.; Gálvez, J.C. The Use of De-Icing Salts in Post-Tensioned Concrete Slabs and Their Effects on the Life of the Structure. *Appl. Sci.* **2023**, *13*, 6961. https://doi.org/10.3390/app13126961

Academic Editor: Syed Minhaj Saleem Kazmi

Received: 20 April 2023
Revised: 5 June 2023
Accepted: 6 June 2023
Published: 9 June 2023

1. Introduction

The use of de-icing salts during low-temperature periods in structures either without a waterproof treatment or a deficient one might result in the entrance of chloride ions through the upper face of their decks. Furthermore, this phenomenon may be aggravated by the presence of other previous relevant concrete pathologies such as pores, hollows or cracks inside the concrete which may ease the circulation of aggressive chemicals until steel reinforcements bars.

This article aims to show the role of de-icing salts in the corroding process of steel rebars and their effects on post-tensioned elements. Consequently, this article pays special attention to the brittle rupture phenomenon of transversal rebars for being extraordinary, as well as highlights the most likely mechanisms that gave rise to this pathology and emphasizing the important use of waterproofing treatments, not only to reduce brittle rupture failures of the steel rebars but also to prevent alkali–aggregate reactions of concrete. The article focuses on a representative case where this process has been observed. The Nudo de Colmenar Bridge, a motorway junction located in the north of Madrid Region with winter road maintenance activities based on the spreading of de-icing salts with concentrations varying from 10 to 15 g/m^2.

The science and engineering in corrosion of reinforced and post-tensioned concrete structures have been developed for more than half a century. The processes of study are slow and need decades to manifest and this means that continuous inspections are needed in order to detect the appearance of durability issues on the structure. Some maintenance tasks, such as the use of de-icing salts to avoid ice and snow in road structures, can be cheap and effective in the short term although they can be disastrous in the mid-term as shown in this study. In social terms, the tremendous financial burden caused by corrosion receives little attention in comparison with health or climate change even though they can be of similar or even greater impact in terms of costs [1]. Additionally, some educational challenges appear in this aspect, showing that civil engineers are generally not well trained to address these challenges This study shows a case study on the effects of the continuous use of de-icing salts in post-tensioned slabs and structures and the reduction of the life span, showing that the study of new alternatives to de-icing salts should be addressed for road maintenance tasks.

1.1. State of the Art

The need for the use of this type of salt, despite the negative chemical impact on concrete, is widespread throughout the world's infrastructure management. For this reason, many studies focus on the analysis of these salts, such as the one carried out by Sanchez Thomas et al., which analyzes the behavior of the main de-icing salts applied in infrastructure maintenance, modifying external conditions such as temperature or W/C ratio [2]. Other authors such as Guoju Ke et al. developed a decision procedure based on the analytic hierarchy process (AHP) to select the most suitable de-icing salt to be used [3]. Other outstanding studies detail the effect on the concrete using hardened cement paste modified with sodium silicate [4].

Regarding the study of post-tensioned concrete slabs, most published research focuses on a physical analysis of those elements, studying, for instance, the impact of loads on the structure. In this sense, research such as that of Youmn Al Rawi et al. stands out, as it analyzed the impact of loads produced by factors, such as rock fall during construction, comparing reinforced concrete slabs (RC) versus post-tensioned (PT) slabs [5]. Similar publications were presented by A. Jahami et al., which studied the load's impact on rehabilitated concrete slabs [6].

Focusing on a more economic aspect related to post-tensioned elements, there are also outstanding publications that detail an economic optimization of them, as is the case of the authors Yakov Zelickman and Oded Amir [7]. Such a study presents a methodology based on computational methods to save up to 50% of the budget and quantity of post-tensioned tendons [7].

However, over-cited studies outstand the ones related to analyzing de-icing salts and their effect on concrete. In this respect, authors such as Luping Tant et al. performed a long-term analysis of chloride penetration and reinforcement corrosion in highway concrete elements exposed since 1990 [8]. Other authors such as Meijie Xie et al. focused on the development of numerical models to predict chloride ingress in concrete subjected to atmospheric carbonation and de-icing salts usage [9]. In line with those investigations, authors such as Sara Al Haj Sleiman et al. study the performance of concrete in freeze–thaw filled exposure [10]. This study outlined the lack of normative methods related to concrete characterization in the presence of de-icing salts [10]. Authors such as Aref Ebrahimi et al. or Jan Deja focused on the concrete properties variation considering freezing and de-icing effects on them [11,12]. Special infrastructure types with outstanding exposure conditions are analyzed by authors such as Mullapudi, R., who focused on typical parking structure problems [13].

The current state of the art houses significant research focused on scientific aspects, as has been detailed previously. However, the novelty of this paper and its contribution to the state of the art relies on the engineering perspective that it provides. The reality of infrastructure management demands quick decision making based on inspections and expertise, with a lack of laboratory data analysis. In this sense, the paper aims to provide an overview of it and complement the research field, which is mostly focused on chemical or physical analysis.

1.2. Previous Experience

In the case of post-tensioned concrete slabs, chemical agents may gain entry into their sheaths, thus corroding their strands. This phenomenon has been observed by the investigation authors in several structures whose repair process was carried out in 2020 and was designed with concrete post-tensioned slabs without any waterproof treatment. In addition, these structures may also suffer an aggregate–alkali reaction causing the deterioration of the concrete.

In these structures, the most relevant damage was several longitudinal cracks observed on the upper face of their decks with numerous transversal broken rebars aligned with the mentioned cracks. Having studied the type of rupture of these rebars, apparently, without any previous elongation, it can be said that the brittle fracture was caused by a corrosion fatigue mechanism. Indeed, this process can be explained because of the combination of the rebars whose cross sections have been previously fragilized by the entrance of chloride ions through cracks with other mechanical concomitant loads (cyclic traffic loads and additional tensile load from concrete expansion) that together may produce the brittle fracture of the entire rebar cross-section.

2. Methodology

This paper focuses on the role of de-icing salt and its effects in a specific infrastructure located in Madrid. In order to archive this goal, various phases were followed. First, a complete description of the infrastructure must be done. Geometric and cross-section properties were defined, highlighting the structural typology and tendons characteristics. This information was relevant for the engineering team, in charge of the visual and special inspections, which are the next phases to commit.

Once the bridge was defined, the team proceeded with an initial visual inspection where the main damages were identified, including, for example, the ones related to the aggregate–alkali reaction. After that, a special inspection was carried out. In this sense, specific aspects such as the assessment of concrete mechanical characteristics, the microscopy analysis of concrete or the connectivity between venting pipes and prestressing sheaths were studied. The aforementioned phases are described as follows, including outstanding aspects that are necessary to obtain results underpinning the decision making.

The importance of periodic inspection phases is highlighted in this study. In this sense, there are different regulations that emphasize the definition of such inspections; for example, the guide to basic inspections of road works for the state road network of Spain or the guide for carrying out main inspections of crossing works on the state road network, both developed by the Ministry of Transport, Mobility and Urban Agenda (MITMA) [14,15]. These guides show three types of inspections: (1) basic, which could be assimilated as a visual inspection; (2) main inspection, or detailed visual inspection; and (3) special inspection. According to the referred guideline, maintenance operations and ordinary conservation activities are executed considering the results obtained from previous inspections [14,15]. Moreover, specific sheets for road maintenance are provided by the cited guide, securing the correct data collection during the inspection phases.

Infrastructure management is progressively gaining importance compared with design. Guides for basic inspection of road works or main inspections of crossing works and flyover bridges [14,15] were released in 2012, whereas the first version of the standard 3.1-IC of road layout design was released in 1939 [16]. The existence of specific regulations for infrastructure management denotes its growing importance in the civil engineering sector, which traditionally focused on the design and construction of new projects. The great social impact of maintenance has become as important as the design of the infrastructure itself. In this sense, the referred document shows the process followed to carry out maintenance in accordance with the indications of the existing regulations.

3. Infrastructure Inspection and Monitoring Carried Out

3.1. Infrastructure Description

The so-called Nudo de Colmenar Bridge (Madrid) connects the M-607 road (Madrid Way) and the M-40 ring road (A-1 Way). The structure is located in the Nudo de Colmenar detailed in Figure 1.

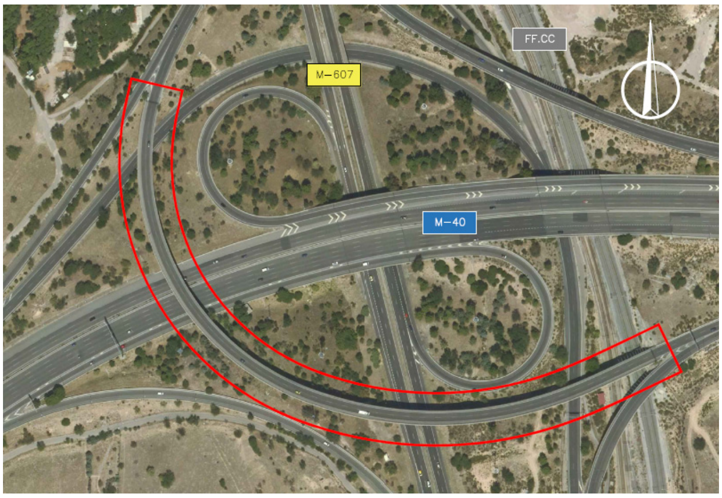


Figure 1. Structure location in the road junction Nudo de Colmenar.

The structure runs over several infrastructures, including the aforementioned highways M-40 ring road, M-607 road and connecting branches, as well as railway lines. It is a hyperstatic overpass whose typology is a continuous post-tensioning concrete slab. Its ground plan is curved. The structure has a total length of 561 m distributed in 17 spans with the following lengths: 20.5–32.2–35.6–37.9–56.4–32.9–36.7–39.0–28.8–29.6–36.5–28.6–30.3–32.9–33.1–28.4–21.6 m. These lengths were taken from the topographic survey carried out during the repair works made on the structure.

The cross-section is constant along the entire length of the deck. The slab has curved geometry with a maximum thickness of 1.40 m at the deck axis that is reduced to 0.20 m at the edge of the deck using a circular segment. The section is composed of a set of six circular lightning elements of variable diameter between 0.65 m and 1.00 m, as can be seen in Figure 2.

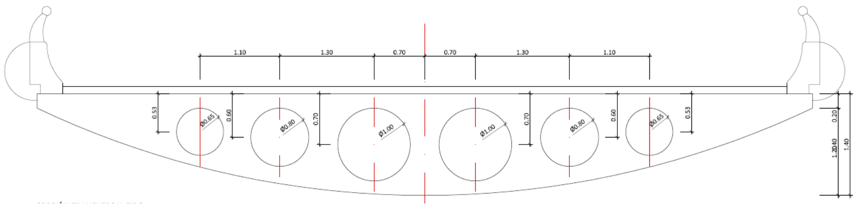


Figure 2. Cross-section of Nudo de Colmenar Structure.

The prestressing in the spans is not constant due to their different lengths, changing from 9 tendons of 15 Ø 0.6″ in the short spans to 16 tendons of 19 Ø 0.6″ in the longer spans.

3.2. Pathologies Detected in the Visual Inspection Initial Phase

The evaluation of the conservation status of a structure and the early detection of damage requires the realization of programmed and systematized inspections, which make it possible to know the structure's performance level at a specific time. Therefore, it is essential to define a conservation strategy that, in addition to other aspects, establishes the inspection levels and frequency with which they are carried out. With this purpose, different inspection levels can be defined according to the personnel that carry them out, the material resources used and the frequency with which they are executed.

The aim of this article is not to define the management of the structure's conservation. However, is important to highlight the importance of carrying out scheduled and systematized inspections, considering that they are a fundamental aspect of the early detection of pathologies and the starting point for the subsequent phases of study and evaluation.

In the case of the structure under study, the first alarm about the conservation status was detected within these programmed inspection works. During the main inspection (visual inspection by expert structural technicians, without special means of access and carried out every 4 years) excessive deflections in some spans and abundant cracking in the deck were noticed. In this way, the detection of the above damages within the programmed inspection works constitutes the first alarm about the state of conservation and gives rise to the subsequent evaluation phase. In this evaluation phase, a detailed visual inspection was carried out by engineers specializing in structural pathology, and a campaign of auscultation and testing was performed. The goal of these tasks was to determine the real scope of the pathologies detected and to assess their implications in the structural safety rate.

Thanks to the previously cited scheduled and systematized inspections, the identified damages revealed the existence of a serious pathological process were, fundamentally, the presence of a concrete degradation process by an aggregate–alkali reaction. It manifested itself in a series of particular damages, including the cut-off in the transverse reinforcing bars of the deck upper face and injection defects of the post-tensioning sheaths.

The process of concrete degradation by an aggregate–alkali reaction was manifested in the following observable damage:

Abundant longitudinal cracking on the bottom surface of the section, oriented parallel to the main prestressing compressions, can be seen in Figure 3.

Figure 3. Longitudinal cracking on the bottom surface of the deck.

Vertical marked deflections, especially in three spans: span # 5 (longest span over the M-40) and spans # 8 and # 11. The deformation of these spans pointed to a loss of concrete stiffness because of aggregate–alkali degradation. This deformation can be observed in Figure 4.

Figure 4. Marked deflections in spans # 5 and # 8 of Nudo de Colmenar structure.

Longitudinal cracks in the deck's upper face coincide with the direction of the prestressing. These cracks, detailed in Figure 5, were observed after milling the pavement.

Figure 5. Longitudinal cracks in the deck's upper face.

Moreover, in addition to the cracks observed on the deck's upper face, cores were extracted in the alignment of the cracks with internal fracturing of the concrete mass. In the visual examination of the cores extracted in the alignment of the fissures, the presence of a white halo around some aggregates was observed, as can be seen in Figure 6. It was compatible with the formation of silica gel of expansive nature, as a result of the aggregate–alkali reaction.

Figure 6. White halos around aggregates detected in the cores without microscopy needed.

Furthermore, sectional cuts in the transverse reinforcement bars were observed with a crack alignment coinciding with some of the longitudinal cracks and with a macroscopic appearance of brittle fracture, according to Figure 7. For the observation of the reinforcement, small test cuts were made in the alignment of the deck cracks.

Figure 7. Sectional cuts in the transverse reinforcement bars.

This type of brittle fracture is probably the most relevant damage observed in the structure under study, due to the extraordinary and unexpected nature of the phenomenon. As can be seen in Figure 7, necking is not observed in the breakage of the bars. In this sense, this fact points directly to a brittle fracture compatible with a corrosion fatigue phenomenon, which suggests the existence of a localized corrosion attack by chlorides coming from the winter maintenance treatments. Chlorides can easily penetrate inside the concrete mass through the existing cracks in the deck's upper face until they reach the reinforcement bars. Multiple factors such as the width or depth crack affect that penetration. However, the paper does not focus on internal chloride diffusion. Consequently, the modeling of chloride penetration is out of the scope of this paper, and we direct the reader to the listed references [17,18].

Lastly, signs of possible injection defects of the post-stressed sheaths were observed by examining the uncovered venting pipes in the milled area, by inserting a tape measure or a screwdriver inside them to check if they were clogged, as detailed in Figure 8. In this preliminary check it was observed that several of the venting pipes were not grouted up to the top face of the slab and that, therefore, it would be likely that there could be an inadequate injection of the prestressing sheaths. This led to the subsequent inspection with a borescope in the auscultation and testing campaign carried out in the structures.

Figure 8. Venting pipes check to verify the clogged conditions (see the handle of the screwdriver inserted into the hole).

In addition to the above pathologies, it should be noted that the presence of any waterproof treatment on the upper face of the deck was not observed. It certainly contributes to aggravating and accelerating any degradation process of the structure. Thus, the above damages, detected in the initial study phase of the state of conservation of the structure, pointed to the existence of a concrete process degradation by an aggregate–alkali reaction, which gave rise to several longitudinal cracks. Additionally, significant vertical deflections appeared because of the loss of stiffness of the concrete characteristic due to advanced stages of the process of arid–alkali degradation.

Additionally, and as will be seen below, the appearance of brittle failure of the upper transverse reinforcing bars with a failure alignment coinciding with the longitudinal cracks was observed. It suggests that the bar's failure is the consequence of a corrosion fatigue phenomenon. This phenomenon occurred as a result of chloride from the frequent use of de-icing salts that go into the slab cracks and the presence of cyclic traffic loads. In addition, the presence of wetting and drying cycles can affect the concrete internal movements of chlorides toward the surface [19].

The use of de-icing salts in post-stressed slabs without waterproof treatment could contribute to the progression of serious damages in the prestressing such as corrosion or even wires breakage. Although these defects were not observable in the initial inspection phases, they could be detected using borescope inspection in the following auscultation phases, as detailed in the following sections.

3.3. Special Inspection

The identification of the previous damage during the visual inspection gives rise to research on the structure to determine the extent of the damage and its real effect on the structural safety index. The research was based on the following process.

Determination of the concrete mechanical characteristics (modulus of elasticity and strength): analyzing its composition and making an electron microscopy observation, providing pictures like the ones shown in Figure 9. In both cases, the results confirmed the existence of an aggregate–alkali reaction in all the extracted cores.

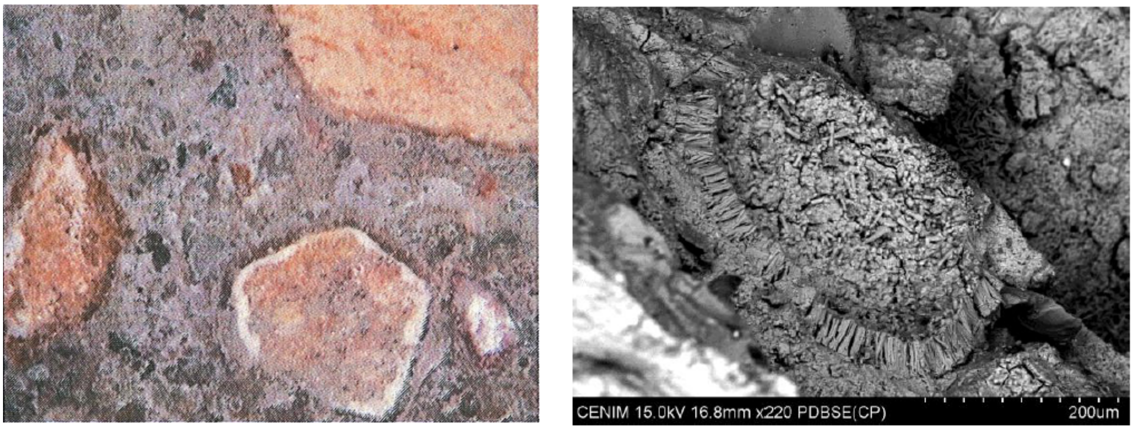


Figure 9. Appearance of the gels detected by microscopy.

In the case of the Colmenar Bridge, all the cores extracted showed, to a greater or lesser extent, fractured aggregates partially altered by chemical degradation processes, with the presence of pores and aggregate–lime interfaces clogged with whitish deposits. Likewise, a 54% average loss of elastic modulus was determined in the cores extracted.

Determination of the chloride content and other processes of a chemical attack on the concrete, observing a very high chloride content in some of the cores extracted (1.57% referred to concrete compared with 0.2% admissible according to the Spanish Structural Concrete Standard EHE-08).

In this sense, the analysis of chloride penetration is particularly important in the case of post-stressed concrete slabs because it can cause the corrosion of the post-tensioning strands, especially when these have injection deficiencies and other execution defects, as will be seen later on. The lack of an adequate waterproof treatment of the deck is also a determining factor in these cases.

In addition to the venting pipes check carried out in the initial phase and visual examination of some areas of prestressing elements, an inspection of the post-tensioning strands was carried out by using a borescope to evaluate the slurry and post-tensioning strand's condition.

The main damage detected in this inspection was some bad connections between the venting pipes and the sheaths (lack of drill holes in the sheath), incomplete filling of the sheath to a greater or lesser degree depending on the areas, leaving unprotected strands both in high points and adjacent sections, corroded and even broken strands due to a stress–corrosion process, slurry exudation and others. Figure 10 shows some examples of the previously mentioned damages. It was also observed that the layout elevations in high points were different from the design elevations, with a vertical displacement of the tendon axis with respect to the theoretical elevation up to 220 mm.

Figure 10. On the left, corroded cords and broken wires; on the right, unusual grout consistency with foam formation.

Defects that revealed malpractice in the execution of the prestressing, such as the presence of venting pipes simply supported on the sheath without any connection hole, were also observed, as shown in Figure 11.

Figure 11. Lack of connection between venting pipe and prestressing sheath (Colmenar Bridge).

4. Results and Evaluation

The detailed visual inspection carried out in conjunction with the research allowed for detecting and ratifying the existence of serious damages in the structure, which were concomitant with other execution defects. In this sense, the most relevant damage detected in the structure means a serious problem in post-stressed concrete slabs due to their implications on structural safety, are the following:

- Concrete degradation process due to aggregate–alkali reaction, chloride contamination because of the use of fluxing salts and lack of waterproofing of the deck;
- Systematic breakage of the transverse reinforcement due to a corrosion–fatigue process;
- Damage to the prestressing strands with a stress corrosion phenomenon and, consequently, the breakage of some wires.

The above damages mean a significant reduction of the safety conditions of the structure. However, although the structure under study had other minor defects, the previous ones have been highlighted because of the relation between them and the extraordinary and unexpected phenomenon of brittle fracture in transverse steel bars, which is described below.

Thus, the deterioration process of the structure began with a concrete sensitive to the aggregate–alkali reaction, that is, concrete with potentially reactive aggregates (reactive silica) that, in the presence of water and the alkalis from the cement paste, gave rise to the formation of an expansive gel that produces internal stresses in the concrete mass. In this sense, the lack of a waterproof treatment played a determining role in the activation of the aggregate–alkali reaction, since for this to occur it is necessary to provide water (usually from an external source); therefore, it is possible to slow down, or even stop this reaction by minimizing the entry of water into the structure, meaning with appropriate waterproofing.

The internal stresses that occur in the concrete as a result of the aggregate–alkali reaction, caused a high number of cracks, that in a massive element or idealized model would form a homogeneous and multidirectional cracking network, but in resistant elements such as bridge decks, the orientation of these cracks is conditioned by the geometry of the element and the orientation of the stresses. In the case of the structure presented in this article, cracks showed a parallel direction to the compression isostatics lines.

The longitudinal cracks observed with large crack openings (over normative limits) together with the lack of an adequate waterproof treatment cause the entry of chlorides from the de-icing salts used during winter into the structure, easing the corrosion of the passive bars and post-tensioning strands.

The bars of the transverse reinforcement showed full-section ruptures with a brittle appearance. In this sense, although the breakage of steel elements by a stress corrosion process is certainly a common phenomenon, in the case of the Colmenar Bridge, these breaks are completely different from the usual forms of breakage due to chloride contamination, which appears as local corrosion that progresses inwards the bar in an inverted cone form.

In the structure covered by the paper, the bars showed a macroscopic appearance of brittle fracture that pointed to the presence of mechanical actions concomitant with chloride attack. Although the breaks detected in the bars are still being analyzed using tests in specialized laboratories, the most likely hypothesis is that it is a corrosion–fatigue phenomenon, in which the steel bars breakage was caused by the simultaneous action of cyclic stress and the presence of an aggressive medium that caused localized corrosion of the steel. Indeed, the presence of cyclic loads associated with traffic on the structure would lead to the crack progression in the pitting of the steel bars caused by the chlorides. In this case, unlike stress corrosion processes, in which the presence of a permanent—or static—stress is necessary for material rupture to occur, in corrosion–fatigue processes this stress must be cyclic. In the case studied, it does not seem reasonable to attribute the rupture of the bars to a stress corrosion phenomenon, since they are not bars with a high level of stress and, in this case, the rupture plane would have the appearance of a quasi-fragile rupture.

Finally, the entry of chlorides through the longitudinal cracks, aggravated by the lack of a waterproof treatment and the injection defects of the post-tensioning sheaths, caused corrosion to reach the strands in certain sections, even causing the break of some of them due to stress corrosion cracking. It should also be noted that in any prestressing inspection, there is a high degree of uncertainty about the reliability of the preservation state since it is an element that is not accessible for inspection at 100% of its length and, therefore, it is necessary to consider this uncertainty in the assessment of the structure preservation state and the final repair proposal.

5. Discussion: Strategies for Prevention and Repair

The above pathologies are a serious problem in post-stressed slab bridge decks. However, for these pathologies to occur, a confluence of several factors is necessary, as is detailed in Figure 12.

The absence of adequate waterproofing to prevent the entry of water into the structure and the penetration of chlorides from the use of de-icing salts played a determining role in the progress of the above pathologies. In this sense, in addition to the presence of reactive silica and alkalis, the presence of water coming from an external source was necessary for the aggregate–alkali reaction to occur. The reaction would cease when one of the above reagents is consumed.

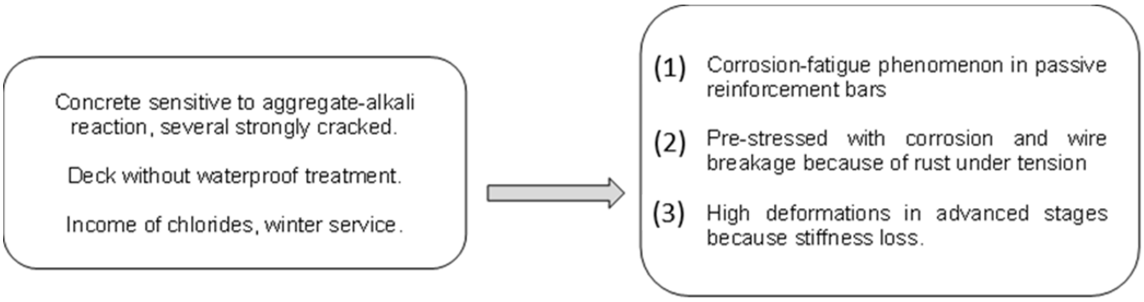


Figure 12. Damage and causal factors.

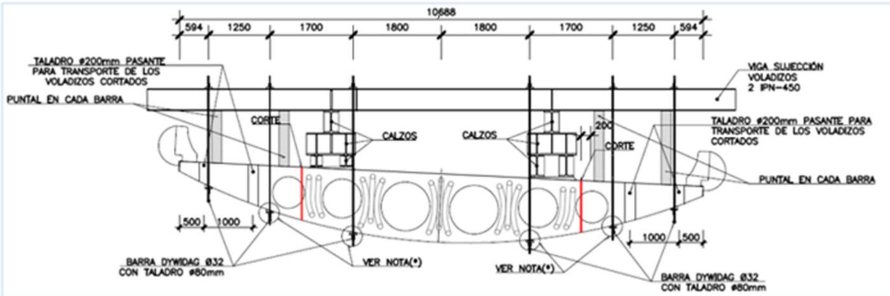
Additionally, the corrosion processes of the passive reinforcement and post-tensioning strands need the presence of an aggressive medium to prosper. In this case, the absence of a waterproofing treatment on the deck facilitated the penetration of chloride ions into the structure, aggravating this process in the previously cracked areas of the deck, where the corrosion rate increased due to the high percentage of chloride entering through the cracks.

Considering the above, it is simple to deduce that an adequate execution of waterproofing in the structure execution phase is a determining factor to avoid the progression of the above pathologies. However, in existing structures with a lack of or deficient waterproofing in which the damage has already progressed and led to pathological evolution, repair strategies based on the restitution of the affected areas and the complete encapsulation of the structure should be chosen. In this case, an appropriate repair strategy would consist of the following elements or phases:

- Hydro-demolition of the deck until the affected transverse reinforcement is revealed. Replacement of the reinforcement and reconstruction with fine aggregate concrete up to the initial level;
- Reinjection of prestressing sheaths by vacuum injection using a fluid slurry with corrosion inhibitor improves their durability significantly;
- Execution of an ultra-high performance concrete layer (UHPCFR) for the encapsulation of the structure of approximately 3 cm to improve structure performance in terms of durability due to its high compactness and the almost total absence of pores. In addition, it provides a further improvement of the structure's performance against transverse bending due to the high performance (up to 150 MPa compression and 12 MPa flexural bending) and multidirectional strength behavior.

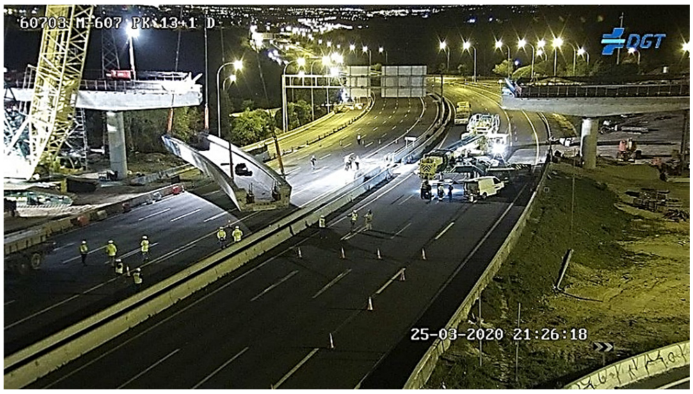
The case of the Nudo de Colmenar Bridge is detailed in the present paper. As a professional project, the paper outlines a decision-making process based on engineering aspects rather than pure scientific data or laboratory results. In the practice of such projects, the decision-making process is commonly done without reduced scientific data support due to a lack of time. This fact is reflected as a limitation of the present paper, where aspects such as brittle fracture are determined by previous experience. Further studies would support brittle fracture or arid–alkali degradation with laboratory analysis results.

Due to the extension and evolution of the pathologies detected, and also the serious damage in the prestressing, it was concluded that the most reasonable alternative was the complete demolition of the bridge and subsequent reconstruction with a new prefabricated concrete deck. Real images of the described process are shown in Figure 13.



(**a**)

(**b**)



(**c**)

Figure 13. Dismantling of existing deck and assembly of new deck over M 40 road. (**a**) Section of the bridge, (**b**) real image of bridge, and (**c**) real image of operation process.

6. Conclusions

The pathologies observed in the structure constitute a serious problem that has progressed due to the confluence of several factors. The lack of waterproof treatment of the structure facilitated the chloride ions penetration from the use of de-icing salts as well as the degradation of the concrete by the aggregate–alkali reaction and the corrosion processes of the passive reinforcement and the prestressing.

In this degradation process, the internal stresses caused by the aggregate–alkali reaction led to the appearance of longitudinal cracks on the upper face of the deck. De-icing salts concentrated and went into these cracks, making easier the corrosion processes of the passive reinforcement and the prestressing cables. The propagation of this aggressive medium together with the concomitant mechanical loads caused brittle breaks in the transversal reinforcement bars. In this respect, although research is currently being carried out in specialized laboratories to determine the most probable cracking mechanisms, everything points to a corrosion fatigue phenomenon, in which the cyclic traffic loads were what induce the propagation of the cracking front with the added tensional load of the expansion of the concrete due to the aggregate–alkali reaction.

Furthermore, although this pathology has only recently been observed in the structure presented in the article, it is not an unusual phenomenon, but it has been observed in other bridges of a similar typology as well (as a result of identifications made in the Colmenar Bridge).

The above pathologies are the result of the confluence of several factors. However, water presence plays a determining role in the deterioration process. In this sense, an appropriate conservation strategy involves minimizing water entry into the structure throughout its service life. For this reason, the execution of high-performance waterproof treatments during the construction phases is a key aspect to avoid the progression of the previous pathologies and their effects on structural safety which, in cases such as the present Colmenar Bridge case, can be irreversible. Similarly, in existing structures without waterproofing in which these pathologies have already progressed, it is possible to slow down the deterioration rate by adopting measures aimed at restoring the deteriorated areas and encapsulating the structure using ultra-high-performance concretes. However, in this case, it will be essential to carry out a research and testing campaign to determine the magnitude, area and evolution degree of the pathologies detected. It will be used to assess the uncertainty about the reliability of the conservation status of the entire length of the prestressing since it is an essential element for the structural safety of the bridge but inaccessible for the complete inspection.

Author Contributions: Conceptualization, T.L.R.A., M.G.A. and N.C.M.; methodology, M.G.A., J.C.G. and R.M.P.; software, M.G.A., J.C.G. and R.M.P.; validation, M.G.A., J.C.G. and R.M.P.; formal analysis, M.G.A., J.C.G. and R.M.P.; investigation, T.L.R.A. and N.C.M.; resources, M.G.A., J.C.G. and R.M.P.; data curation, T.L.R.A. and N.C.M.; writing—original draft preparation, T.L.R.A. and N.C.M.; writing—review and editing, M.G.A., J.C.G. and R.M.P.; visualization, M.G.A., J.C.G. and R.M.P.; supervision, M.G.A., J.C.G. and R.M.P.; project administration, T.L.R.A. and N.C.M.; funding acquisition, T.L.R.A., M.G.A. and J.C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declared no conflict of interest.

References

1. Angst, U.M. Challenges and opportunities in corrosion of steel in concrete. *Mater. Struct.* **2018**, *51*, 4. [CrossRef]
2. Sanchez, T.; Conciatori, D.; Keserle, G.C. Influence of the type of the de-icing salt on its diffusion properties in cementitious materials at different temperatures. *Cem. Concr. Compos.* **2022**, *128*, 104439. [CrossRef]
3. Ke, G.; Zhang, J.; Tian, B. Evaluation and selection of de-icing salt based on multi-factor. *Materials* **2019**, *12*, 912. [CrossRef] [PubMed]
4. Skripkiūnas, G.; Nagrockienė, D.; Girskas, G.; Janavičius, E. Resistance of modified hardened cement paste to frost and de-icing salts. *Balt. J. Road Bridge Eng.* **2012**, *7*, 269–276. [CrossRef]
5. Al Rawi, Y.; Temsah, Y.; Baalbaki, O.; Jahami, A.; Darwiche, M. Experimental investigation on the effect of impact loading on behavior of post-tensioned concrete slabs. *J. Build. Eng.* **2020**, *31*, 101207. [CrossRef]
6. Jahami, A.; Temsah, Y.; Khatib, J.; Baalbaki, O.; Darwiche, M.; Chaaban, S. Impact behavior of rehabilitated post-tensioned slabs previously damaged by impact loading. *Mag. Civ. Eng.* **2020**, *93*, 134–146.
7. Zelickman, Y.; Amir, O. Optimization of post-tensioned concrete slabs for minimum cost. *Eng. Struct.* **2022**, *259*, 114132. [CrossRef]
8. Tang, L.; Boubitsas, D.; Huang, L. Long-term performance of reinforced concrete under a de-icing road environment. *Cem. Concr. Res.* **2023**, *164*, 107039. [CrossRef]
9. Xie, M.; Dangla, P.; Li, K. Reactive transport modelling of concrete subject to de-icing salts and atmospheric carbonation. *Mater. Struct.* **2021**, *54*, 240. [CrossRef]
10. Al Haj Sleiman, S.; Izoret, L.; Alam, S.Y.; Grondin, F.; Loukili, A. Freeze–thaw field exposure and testing the reliability of performance test temperature cycle for concrete scaling in presence of de-icing salts. *Mater. Struct.* **2022**, *55*, 2. [CrossRef]
11. Besheli, A.E.; Samimi, K.; Nejad, F.M.; Darvishan, E. Improving concrete pavement performance in relation to combined effects of freeze-thaw cycles and de-icing salt. *Constr. Build. Mater.* **2021**, *277*, 122273. [CrossRef]
12. Deja, J. Freezing and de-icing salt resistance of blast furnace slag concretes. *Cem. Concr. Compos.* **2003**, *25*, 357–361. [CrossRef]
13. Mullapudi, R. Typical Parking Structure Problems, Repairs, and Cost Assessment. In Proceedings of the Ninth Congress on Forensic Engineering, Denver, CO, USA, 4–7 November 2022; pp. 960–968.
14. Guía de Inspecciones Básicas de Obras de Paso. Available online: https://cdn.fomento.gob.es/portal-web-drupal/inspecciones_obras_paso.pdf (accessed on 1 May 2023).
15. Guía Para la Realización de Inspecciones Principales de Obras de Paso en la Red de Carreteras del Estado. Available online: https://www.mitma.gob.es/recursos_mfom/0870250.pdf (accessed on 1 May 2023).
16. Norma 3.1-IC de la Instrucción de Carreteras. Trazado. Available online: https://apps.fomento.gob.es/CVP/handlers/pdfhandler.ashx?idpub=ICW050 (accessed on 1 May 2023).
17. Guzmán, S.; Gálvez, J.C.; Sancho, J.M. Modelling of chloride ingress into concrete through a single-ion approach. Application to an idealized surface crack pattern. *Int. J. Numer. Anal. Methods Geomech.* **2014**, *38*, 1683–1706. [CrossRef]

18. Guzmán, S.; Gálvez, J.C.; Sancho, J.M. Cover cracking of reinforced concrete due to rebar corrosion induced by chloride penetration. *Cem. Concr. Res.* **2011**, *41*, 893–902. [CrossRef]
19. Bernal, J.; Fenaux, M.; Moragues, A.; Reyes, E.; Gálvez, J.C. Study of chloride penetration in concretes exposed to high-mountain weather conditions with presence of deicing salts. *Constr. Build. Mater.* **2016**, *127*, 971–983. [CrossRef]