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Boosting Durability and Sustainability in Reinforced Concrete Bridges Through the Optimization of the Concrete Cover

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Abstract

Transportation systems play a pivotal role in the economic progress of communities. Within these systems, bridges are crucial for linking regions, facilitating the crossing of obstacles such as rivers and valleys. These structures, however, demand significant human and monetary investments. In the realm of civil engineering, rein-forced concrete bridges stand as monumental feats of design and function. A critical factor in the longevity and eco-friendliness of these structures lies in the concrete cover that protects the reinforcing steel. In this paper, we explore the multifaceted role of concrete cover in not only extending the lifespan of these bridges but also in advancing their sustainability. Properly managing such an infrastructure, including reinforced concrete (RC) road bridges, aligns with multiple United Nations Sustainable Development Goals. Goal #9 focuses on establishing robust infrastructure, encouraging inclusive and sustainable industrial growth, and spurring innovation. Con-versely, subpar and inefficient planning could impede the realization of goal #15, dedicated to the preservation of land ecosystems. Acknowledging the inevitable corrosion issues in reinforced concrete bridges, this paper introduces a sensitivity analysis of the cover protective layer of the reinforcement. A case study of a Portuguese concrete bridge belonging to the A25 highway is presented. A deterioration model is applied for the quantifica-tion of the lifetime and correspondent users' costs of the reinforced concrete bridge of different solutions of rein-forced concrete cover. The sensibility analysis was performed for concrete thickness of 25 mm, 30 mm, 35 mm, 40 mm and 45 mm. Based on the findings of the research it can be concluded that adopting solutions, or materials that provide wider lifespan, of the concrete bridges, will decrease significatively the total costs and environmen-tal impact of the construction of bridges.

Key words: *Concrete Bridges, Concrete Cover, Sustainability*

Introduction

The United Nations report, better known as the Brundtland Report, first formulated the concept of 'sustainable development,' defining it as development capable of meeting current needs without compromising the needs of future generations (United Nations, 1987). The United Nations has been driving sustainability in public policies at international, national, and local levels concerning the 17 Sustainable Development Goals of the 2030 Agenda (Magliacani, 2023). These objectives are visually depicted in Fig. 1.

Fig. 1. Sustainable Development Goals (Magliacani, 2023)

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Sustainable development is a multidimensional policy that integrates six fields of knowledge: political, economic, social, environmental, aesthetic, and cultural (Szarek-Iwaniuk, 2021). The construction sector has a significant environmental, social, and economic impact, as it consumes natural resources, generates greenhouse gas emissions, and influences the quality of life and well-being of populations. The promotion of sustainable construction helps achieve various UN SDGs, such as SDG #13, which focuses on climate action and aims to take urgent measures to combat climate change and its impacts (Sampedro, 2021).

The lifespan of highway infrastructure assets is expectantly long. They are designed and built to last. However, they also face structural aging and degradation due to traffic and environmental factors, natural and human hazards, and changes in demand and functional use. Throughout the life of the asset, many decisions are made from design to replacement. Publicly owned highways and streets are among the most valuable assets in the United States. According to the Bureau of Economic Analysis, they were worth about $4.0 trillion in 2019 (Mallela, J., & Sadasivam, 2023).

A global issue in recent decades has been the worsening condition of infrastructure, which is becoming old, damaged, and prone to collapse during likely disasters caused by nature or humans. Reinforced concrete structures lodge a major share of the infrastructural stock of many countries all over the world (Faroz et al., 2016). Across all sectors, the total cost of corrosion at around 4% of GDP on average in industrialized countries. The specific case of steel corrosion in concrete certainly contributes significantly to this fraction and the sums allocated annually to the rehabilitation of corroded reinforced-concrete structures stands at billions of Euros (François et al., 2018).

The most prevalently used construction material worldwide is reinforced concrete. The diversity of mechanical characteristics and interaction mechanisms of structure components of concrete is responsible for the heterogeneity of the physical properties of the concrete composite (Tijssens et al., 2001). One of the primary reasons for the deterioration of reinforced concrete (RC) structures is concrete cover cracking, spalling and delamination due to rebar corrosion (Su et al., 2015). Reinforced concrete structures can suffer from early damage due to the corrosion of reinforcement, which is one of the main factors that affect their serviceability and durability. The corrosion of reinforcing steel can have a significant impact on the performance and longevity of concrete structures (Bamforth, 2004). Physical and chemical attacks can cause internal expansion in concrete. This can happen when salt or ice forms inside the concrete, or when alkali-aggregate reaction, sulphate attack, or delayed ettringite formation occurs. In RC structures, corrosion of the reinforcement bar due to the electrochemical reaction can lead to volumetric expansion as the volume of the generated corrosion products is larger than that of the original steel and (Zhang and Su, 2017) as represented in Fig 2, one of the main causes of damage and deterioration in concrete structures is the corrosion of the steel bars that reinforce them. This can compromise the safety and durability of the concrete infrastructure (Tian et al., 2023).

Fig. 2. Reinforcement corrosion of a bridge column (American Society of Civil Engineers, 2025)

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Concrete structures that have anomalies related to the corrosion of their reinforcement have become more common in recent years. This can happen when carbon dioxide (CO_2) from the air enters the pores of the concrete and lowers the pH level around the reinforcement, making it more prone to rusting. This process is called concrete carbonation (Monteiro et al., 2012). Carbon dioxide (CO_2) is the main agent that causes carbonation in ordinary Portland cement concrete that is fully hydrated. It enters the concrete as a gas through the pores on the surface and then dissolves in the water inside the pores. It reacts with the calcium hydroxide ($Ca(OH)_2$) in the cement paste and forms calcium carbonate ($CaCO_3$) (Bullard et al., 2011). The steel rebar in concrete is initially protected from corrosion by a passive film that forms around it. However, over time, harmful agents can enter the concrete and break the passive film, causing the steel to corrode. The passive film can be damaged by two different factors: the loss of alkalinity due to carbonation of the concrete, or the accumulation of chloride ions on the steel surface (Jamali et al., 2013).

Carbonation-induced corrosion affects about two-thirds of all structural concrete that is exposed to environmental conditions that are favorable to carbonation, according to (Jones et al., 2000). This type of corrosion is more uniform than chloride-induced corrosion, which is more severe (Köliö et al., 2014).

The types of corrosion that can occur are illustrated in Fig. 3 with a schematic representation. When the concrete is carbonated, it ceases to provide protection to the reinforcements, resulting in widespread corrosion in the affected area. Localized corrosion may result from the action of chlorides or from cracks that occur due to the stress state of the materials.

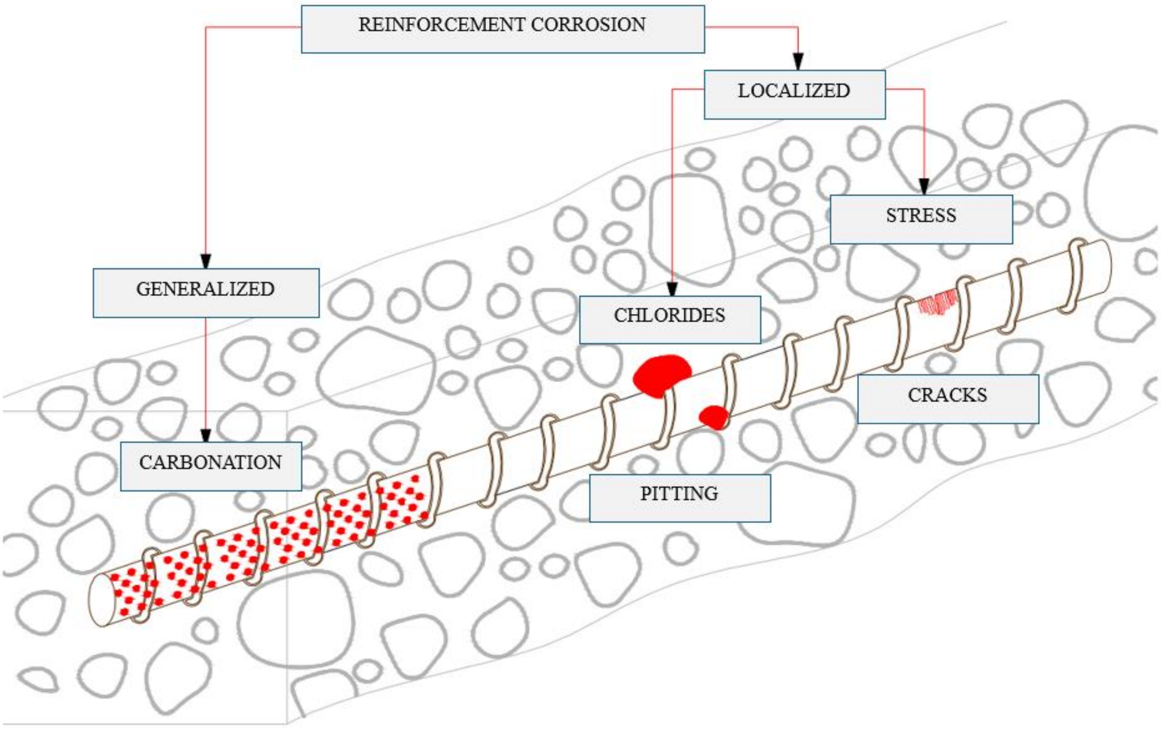

Fig. 3. Reinforcement corrosion types (Salta, 2004)

As the steel corrodes and the concrete covers cracks, the corrosion products fill the pores of the concrete near the steel/concrete interface. These products form a layer of corrosion that builds up between the steel and the concrete (Zhao et al., 2016). This also reduces the cross-sectional area of the rebar, which weakens the structure's strength and ductility affecting their performance and reliability and posing serious safety risks (Freddi and Mingazzi, 2022).

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The influencing parameters that affect crack initiation time the most significantly are the rate of corrosion, thickness of interfacial transition zone, and type of corrosion products (Cui and Alipour, 2018).

Different types of models have been developed to estimate the time until cracks appear due to corrosion, which can be broadly classified into three groups: empirical models (Torres-Acosta and Sagues, 2004), analytical models (Reale and O'Connor, 2012) and numerical models (Du et al., 2014). The empirical models are usually based on statistical analysis of experimental data and use simple mathematical formulas to identify the key parameters. Analytical models are mainly based on fracture mechanics and involve more parameters and mechanistic aspects.

Corrosion reduces the ability of structures to bear loads, which affects their safety and performance (Ma et al., 2013). Cover thickness, stirrup spacing, and aggregate have a significant impact on the spalling of concrete covers (Zhang et al., 2021).

The cover surface bulges depending on how much concrete cracks. When the concrete is not cracked or only slightly cracked, the cover surface bulges less than the rust thickness because the concrete holds it back. It can be stated that the crack opening increases linearly with the increase in the net maximum thickness of the rust (Zhang et al., 2020).

Fig. 4 depicts a range of strategies aimed at enhancing the durability of reinforced concrete structures. These methods are systematically categorized across different intervention levels, providing a holistic framework for improving structural resilience.

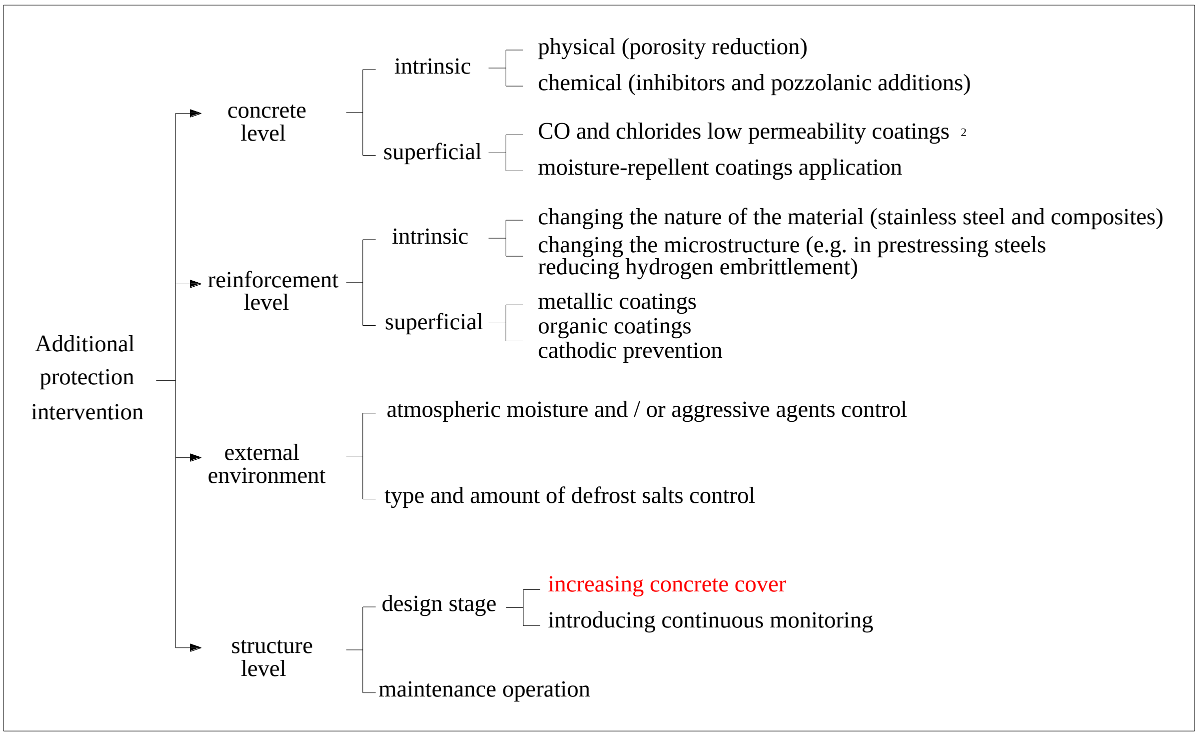

Fig. 4. Additional protection intervention (Salta, 2004)

Methodology

This study investigates the influence of the thickness of the concrete cover in reinforced concrete structures, focusing on the problems caused by carbonation and chloride effects on reinforced concrete roadway bridge decks. The service life of reinforced concrete structures is shortened due to the corrosion effects. The effect of corrosion on structures made with common reinforcements, without any type of protection, leads to the need for maintenance operations in a very short period, which can be as short as only 10 years (Koch et al., 2002).

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In Fig. 5 two graphs are represented, each highlighting a different aspect of the lifecycle of an asset, such as a concrete structure: The top graph represents the condition of the asset throughout its service life. Initially, the condition was excellent, but it gradually declines over time due to wear and deterioration. Sharp drops are visible at specific intervals, representing moments when significant damage occurs, or repairs become necessary. These are followed by partial recoveries, illustrating repairs that temporarily restore the condition but do not bring it back to its original state. Eventually, the condition falls below the critical threshold (C_f), signaling the end of the asset's usable life. The bottom graph details the associated costs during the asset's service life. Early in the timeline, there is a significant expense related to the planning, design, and construction of the asset. Following this, smaller spikes in expenses occur periodically, corresponding to repair or renewal events seen in the top graph. Additionally, there is a steady, ongoing expense for routine maintenance throughout the life of the asset. This graph emphasizes how financial planning for maintenance, repairs, and eventual replacement is crucial. It also enhances that the initial condition has a crucial role in the behavior of the assets.

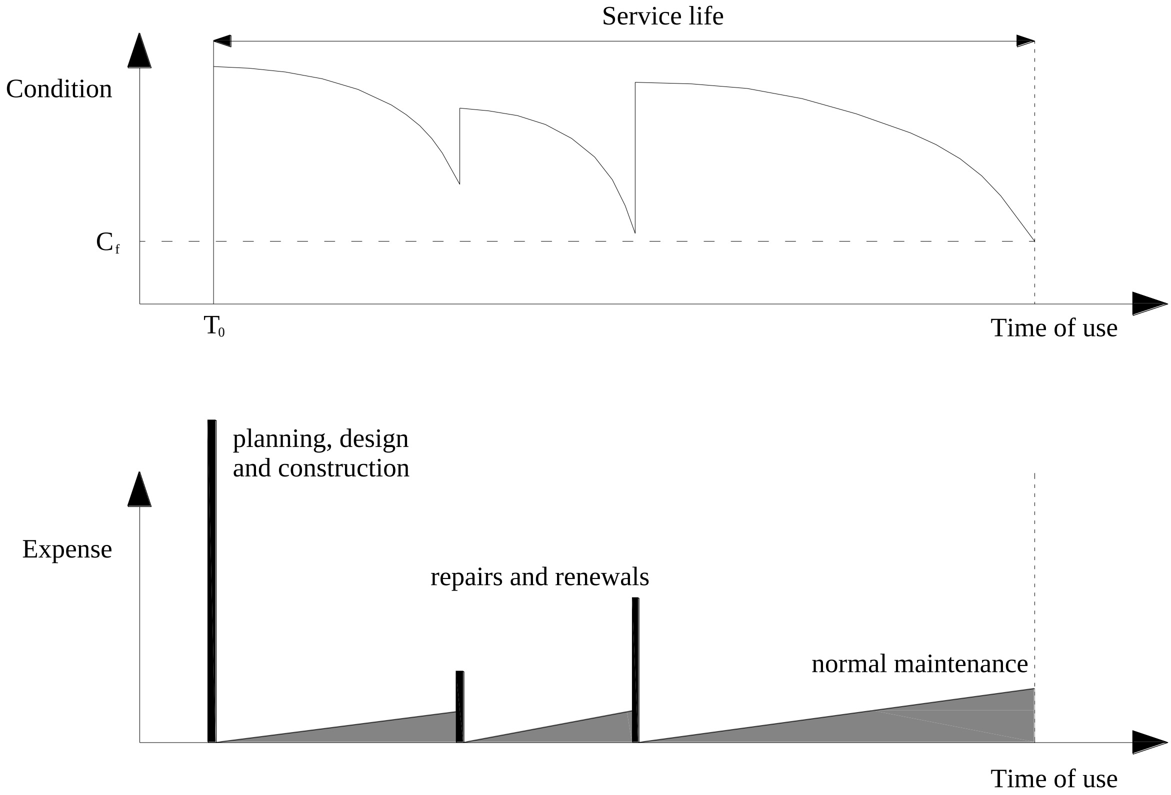

Fig. 5. Condition and expense evolution during the lifetime of a bridge (Hawk, 2003)

The utilized model, defined in (LNEC E-465, 2007) and (Almeida et al., 2011) is based on a probabilistic approach that considers the variability of the input parameters and the uncertainty of the models. The methodology allows the assessment of the minimum propagation period of corrosion, which is the time between the initiation phase and the propagation phase that leads to the cracking of the concrete cover due to corrosion. A more detailed explanation of this method is provided in Tuutti (1982).

It is well accepted that the moisture content plays the most important role in the corrosion rate process (González and Perdrix, 1982).

According to Andrade and Alonso (2001) when the moisture content is low, that occurs when the concrete is in a dry environment, the corrosion rate is below 0.1 $\mu A/cm^2$. This value grows to

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1 μA/cm^2 when the humidity goes up. Temperature also influences how fast corrosion happens (Andrade et al., 2002).

The method used, presented in equation (1), is based on Fick's first law, and allows determining the depth of carbonation.

$$X = \sqrt{\frac{2 \cdot D \cdot \Delta_c}{a} \cdot t \cdot K} \tag{1}$$

Where:

X – depth of carbonation;

D – diffusion coefficient of CO_2 through carbonated concrete in equilibrium with an environment of 65% relative humidity and at a temperature of 20 ºC [m²/year];

Δ_c – concentration differential between the carbonation front and the exterior. This method assumes that all CO_2 is consumed at the carbonation front; using the previously admitted CO_2 concentration, it follows that $\Delta_c = 0{,}7 \times 10^{-3} kg/m^3$;

t – elapsed time;

a – amount of CO_2 that causes the carbonation of the alkaline components contained in a unit volume of concrete; the values assumed by this parameter depend on the type of cement used;

K – parameter that allows considering the curing of concrete and environmental exposures different from 65% relative humidity.

The consequences of the reinforcement cover variation, and its repercussions on the time required for corrosion to occur, are studied both at the level of user costs and accounting for the environmental effects resulting from the emissions of vehicles.

The user costs in work zones are computed and includes all those resulting from the increased operating costs of vehicles and time due to delays subsequent from construction, maintenance, or rehabilitation activities (NJDOT, 2024).

In Fig. 6 Work Zone Impact is represented. The work zone, highlighted in yellow, occupies a section of the road, requiring vehicles to adjust their movement. This adjustment includes changing lanes and reducing speed. The key components affecting the costs due to the traffic flow and efficiency are: Speed Change VOC: Represents the additional Vehicle Operating Cost due to speed adjustments (deceleration and acceleration) before and after the work zone; Speed Change Delay: Indicates the time delay caused by these speed adjustments; Work Zone Delay: Highlights the time delay experienced within the work zone itself, as vehicles traverse at a lower speed.

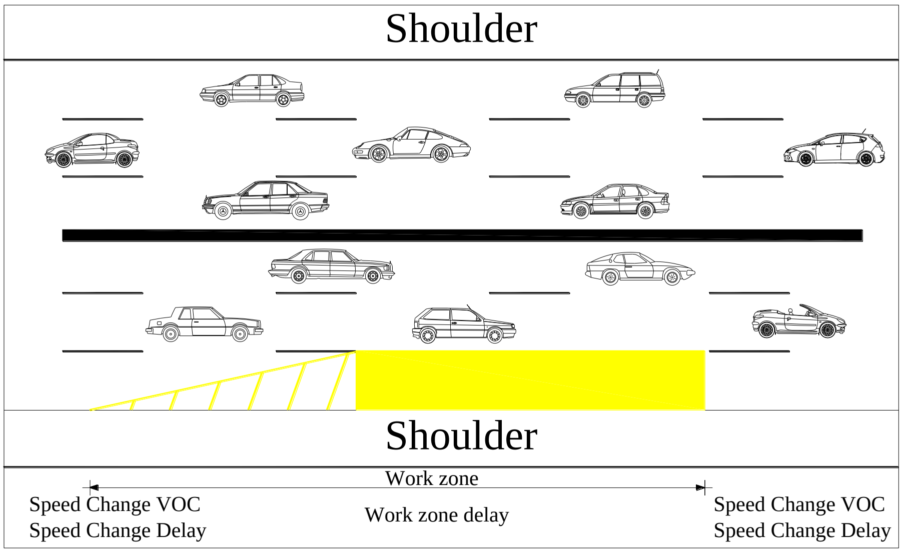

Fig. 6. Work zone related costs (NJDOT, 2024)

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Additionally, costs resulting from an increase in accident rates are added. User costs depend on the opportunity, duration, frequency, scope, and characteristics of the work zone; the volume and characteristics of the operation; the operating costs of vehicles, as well as the unit cost of user time.

Case study

The developed model is applied in a real case study, represented in Fig. 7. The adopted methodology involves determining the updated total costs for the analysis period by quantifying the direct costs and those of the users. The analysis unfolds by defining a possible intervention scenario. For the application of the methodology, it was chosen the bridge over the brook of Cortiçô. This bridge, consists of five spans (22.00 m + 26.00 m + 26.00 m + 26.00 m + 22.00 m), with a total length of 122.00 m. is integrated into the A25, an exploited concession by ASCENDI – Autoestradas das Beiras Litoral e Alta, S.A.

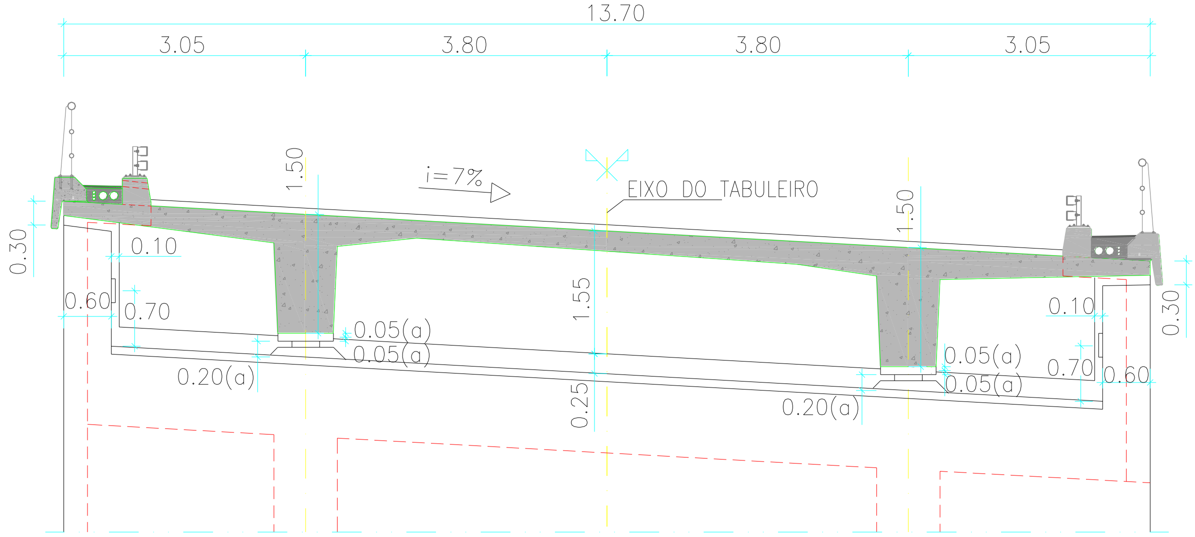

Fig. 7. Cross section of bridge over the Cortiçô brook (ASCENDI, 2003)

The bridge being analyzed is situated between the cities of Guarda and Viseu, more precisely on the Celorico da Beira (pk. 137+800) / Fornos de Algodres (pk. 125+842) section, which has an approximate length of 12.1 km. Considering 100 years as the analysis period, being the design life of the structure, the direct costs and the users' costs were determined for the case study.

Results and discussion

Using the deterioration model, the initiation period of corrosion for the base alternative considered (use of current reinforcements) was determined. The defined repair strategy considers that repairs are implemented at the end of the initiation period. According to EN 1992 (2005), the exposure class considered was XC3. The value of the carbonation front depth was assumed to be the value of the reinforcement cover (X = 30 mm). For the applied materials, e.g. C 30 / 37 S2 XC3 concrete and S 500 NR steel, the computed initiation time was 30 years. Considering the construction year (2005), the specified cover and the utilized materials, in Table 1 the timetable of interventions is presented.

Table 1. *Timetable of interventions*

Service life (years)	Intervention #1	Intervention #2	Intervention #3
30	2035	2065	2095

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In the study, the base scenario used the cover value admitted in the project (30 mm). The sensitivity presented analysis considers the following values for the cover: 25 mm; 30 mm (base scenario); 35 mm; 40 mm; and 45 mm.

The direct costs were quantified considering the lifetime of the repair solution, so the period between interventions is equal to the initiation time of the applied material. When repair operations are carried out, and due to there being restrictions on the free flow of traffic, there may be additional costs to the users. Here a comparative study is made between the costs of the users without accounting for any disturbance due to the existence of works and the costs that occur due to the existence of works. The differential between these costs will be the value attributed to each intervention.

The traffic distribution considered was 75% light vehicles and 25% heavy vehicles. Each of these classes was subdivided into two. The light vehicle class was subdivided into passenger cars and light commercial vehicles. The heavy vehicle class was subdivided into heavy goods vehicles and heavy passenger vehicles. Given that, due to the existence of works, there is the possibility of considerable traffic queues forming, it was assumed there would be a limit to the number of vehicles in a queue. When this limit is exceeded, the additional traffic is redirected by an alternative route, which in this situation is the national road EN 16. The detour considered has 8700 m on the national road, 4600 m on urban roads, and 300 m on access roads. For the diverted vehicles, a study on the formation of waiting queues is carried out.

The computed user costs are the vehicle operation costs, which considered the costs of fuel, tire costs, maintenance and engine oil costs, and depreciation costs. The travel time costs were determined based on the distribution ratio of the purpose of the trips throughout the week; the average monthly earnings of workers in general and of workers in the transport segment; definition of an hourly cost of the trip at work; and definition of a percentage of the cost of non-work trips based on the cost of work trips. The accident costs were calculated considering fatalities, serious injuries, minor injuries, and property damage only accidents. The estimate of the number of accidents was made considering the formulation presented in Lopes and Cardoso (2007) introducing corrective factors such as location and type of road. When applicable, toll costs were introduced, which depend on the vehicle class.

Table 2 presents the variation in alternative lifetimes and the number of interventions with the concrete cover thickness, as well as the correspondent direct and user costs.

Table 2. *Lifetime, the number of interventions and direct costs relationship*

Cover thickness (mm)	25	30	35	40	45
Lifetime (years)	20	30	41	55	70
Number of interventions	5	3	2	1	1
Direct costs	367 895€	265 145€	213 067€	175 678€	161 912€

It demonstrates that as the thickness of the concrete cover grows, so does the structure’s longevity. Fewer interventions are required over time, rendering the solutions not only more cost-effective but also more sustainable for the environment, because of the lesser number of interventions. In Fig. 8 the results of the user costs are plotted, and it can be observed that this trend highlights the economic benefits of increasing cover thickness in reinforced concrete structures. A thicker cover likely provides better protection against environmental factors like corrosion, reducing long-term repair and maintenance costs.

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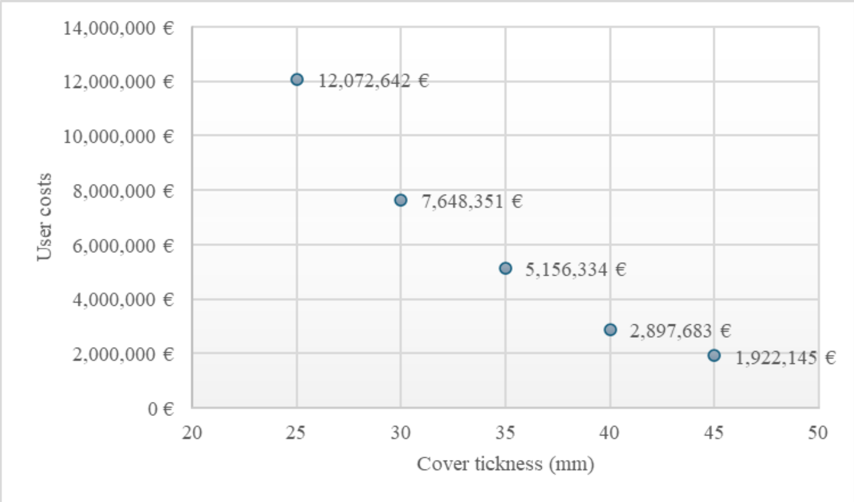

Fig. 8. Effect of concrete cover thickness on user costs in reinforced structures

Conclusions

1. The findings of this research provide a robust framework for predicting the initiation and propagation of corrosion-induced cracks in the concrete cover of reinforced concrete structures. By offering accurate predictions, this approach significantly contributes to assessing and extend-ing the service life of reinforced concrete structures.
2. The longevity of reinforced concrete structures is intrinsically linked to a multitude of fac-tors. These include the strength class of the concrete, the type and dosage of cement, the water-to-cement ratio, curing processes, and the thickness of the reinforcement cover, among others. The predictive calculations and the scenarios developed in this research are grounded in the analysis of the progression of the carbonation front and the infiltration of chlorides. To achieve the desired service life for such structures, it is paramount to maintain stringent quality control over both the construction materials and the methodologies employed.
3. Moreover, the financial implications underscore the importance of proactive measures. The direct costs associated with repair works are significantly lower—by an order of magnitude—than the users' costs. Consequently, adopting structural solutions designed for an extended service life proves to be a more cost-effective approach in the long term. This is particularly true when com-pared to solutions with a shorter lifespan, as user costs dominate overall expenditure.
4. To further enhance durability, it is recommended to implement coatings and surface treat-ments that minimize the frequency of interventions throughout the service life of the structure. Depending on environmental conditions, it is advisable to exceed the minimum regulatory standards for these protective measures, ensuring optimal performance and extended structural longevity. With fewer interventions needed, the direct costs of repairs are reduced, and the user's costs, such as delays or disruptions during maintenance, are significantly minimized. This makes increasing cover thickness a cost-effective measure.
5. It was proven that thicker concrete covers provide enhanced protection to the reinforcement against environmental factors like carbonation and chloride ingress, which are primary causes of corrosion. This improved durability leads to fewer repairs and maintenance interventions over the structure's service life.

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Gelžbetoninių tiltų ilgaamžiškumo ir tvarumo didinimas optimizuojant betoninę dangą

(Gauta 2025 m. kovo mėn.; atiduota spaudai 2025 m. balandžio mėn.; prieiga internete nuo 2025 m. gegužės 9 d.)

Santrauka

Transporto sistemos yra gyvybiškai svarbios ekonominei pažangai, o tiltai atlieka labai svarbų vaidmenį sujungiant regionus ir įveikiant gamtines kliūtis, pvz., upes ir slėnius. Šioms struktūroms reikia didelių žmogiškųjų ir finansinių investicijų. Civilinėje inžinerijoje gelžbetoniniai tiltai yra monumentalūs dizaino ir funkcionalumo pasiekimai. Pagrindinis jų ilgaamžiškumo ir tvarumo elementas yra betoninė danga, apsauganti armatūrinį plieną.

Šiame darbe nagrinėjama betoninės dangos svarba pailginant tiltų eksploatavimo laiką ir didinant jų tvarumą. Tinkamas tokios infrastruktūros valdymas dera su keliais Jungtinių tautų darnaus vystymosi tikslais (DVT). Konkrečiai, 9-asis tikslas skirtas atspariai infrastruktūrai kurti, skatinant įtraukų ir tvarų pramonės augimą bei inovacijas. Kita vertus, prastas ir neefektyvus planavimas gali trukdyti pasiekti 15-ą tikslą, kuris skirtas žemės ekosistemų apsaugai.

Dokumente pripažįstama neišvengiama gelžbetoninių tiltų korozijos problema ir pateikiama apsauginio betono dangos sluoksnio jautrumo analizė. Pateikiamas Portugalijos betoninio tilto A25 greitkelyje atvejo tyrimas. Siekiant

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kiekybiškai įvertinti gelžbetoninio tilto, kurio betono dangos storis yra 25 mm, 30 mm, 35 mm, 40 mm ir 45 mm, eksploatavimo laiką ir susijusias naudotojo išlaidas, taikomas nusidėvėjimo modelis.

Išvados rodo, kad sprendimų ar medžiagų, užtikrinančių ilgesnį betoninių tiltų eksploatavimo laiką, priėmimas gali reikšmingai sumažinti bendras tiltų statybos išlaidas ir poveikį aplinkai. Šis tyrimas pabrėžia kritinį betono dangos vaidmenį tiek gelžbetoninių tiltų patvarumui, tiek tvarumui, akcentuojant tinkamo planavimo ir medžiagų parinkimo poreikį, kad būtų pasiekta ilgalaikė nauda.

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