Reception: **August 12, 2019** | Acceptance: **September 6, 2019**

CORROSION AND STRUCTURAL INSPECTION OF AN INTERNAL REINFORCED CONCRETE ELEMENT LOCATED AT CHAINAGE 0+145 IN THE SAN ROQUE UNDERGROUND CULVERTS-ARCH, IN TUXTLA GUTIERREZ, CHIAPAS

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To quote this article:
Pérez D., José, Godinez D., Eber, Mundo M., Martín., Hernández C., Daniel. (2020). Inspección por corrosión y estructural de un elemento de concreto reforzado interno, que atraviesa al embovedado de San Roque en el cadenamiento 0+145, en Tuxtla Gutiérrez, Chiapas. *Espacio I+D, Innovación más Desarrollo. IX*(22), 150-171. doi: http://dx.doi.org/10.31644/IMASD.22.2020.a08

— Abstract—

Sabinal River crosses the city of Tuxtla Gutiérrez, Chiapas, from west to east, with an approximated longitude of 12 km. This river has 21 tributaries, which over the years and the population growth, the river federal zone and its effluent's have been invaded by the urban spot. Currently, four of these tributaries have been constructed as underground culverts-arch and represent a high risk to the population located close or over this infrastructure, because some sections have more than 50 years without maintenance and have been submitted, internally, to aggressive environment, product of the gases generated by sewage, such as: hydrogen sulfides, methane and ammonium, mainly. Besides carbon dioxide, oxygen and nitrogen, which are common, together with humidity and high temperature which contribute to the accelerated deterioration. This paper presents the analysis of a visual inspection, integrating materials deterioration associated to the structural damage found, in addition to obtained results from electrochemical and chemical test to evaluate the degree of corrosion in a structural element of reinforced concrete that crosses the underground culverts-arch. It is possible to conclude that structure presents different pathologies, classified as common damages such as efflorescence, softened zones, and fungi on bricks and natural rocks, on areas with reinforced concrete, cracking, leaks, efflorescence, lixiviation, infiltration and concrete runoff. Severe damages were observed, such as blowups, partial detachments, generalized corrosion and total loss of steel reinforcement, at some locations, in the main structure. This degradation is active and constant, according to the evaluated electrochemical parameters, which affects the efficiency and durability of evaluated elements in the San Roque underground culverts-arch.

Keywords

Inspection; corrosion; underground culverts-arch; corrosion potential; carbonation; structural pathologies.

Despite his knowledge of construction, man has not been able, until today, to carry out civil infrastructure that does not need to be conserved. Worldwide, structures (buildings, roads, ports, bridges, docks, tunnels, underground culverts-arch, drainage works, etc.), throughout the years, have been observed to suffer environmental impact where they have been built. Corrosion problems and degradation of materials are due to a natural phenomenon, through which chemical systems express their tendency towards a state of stable equilibrium (González, 1989). For this reason, timely inspection and evaluation serve to plan a proper conservation program which can result in a long and efficient service life under extreme environmental and structural loads to which the infrastructure is exposed.

Therefore, this paper presents the analysis of visual inspection and specific chemical carbonation tests, as well as electrochemical measurements of corrosion potentials (ASTM C876-91) performed on an internal reinforced concrete element, which crosses the San Roque underground culverts-arch at chainage 0+145. This investigation was derived from two incursions inside the San Roque underground culverts-arch by a group of specialists in materials science, structures, hydraulics, hydrology, topography and social communication (see the following link on youtube: https://www.youtube.com/watch?v=MkXuOTc_VkI). The main results associated with materials science (corrosion) and structures are presented in this paper.

Civil infrastructure of the underground culverts-arch, with an approximate length of 1,248 m (Figure 1), is composed of various materials, such as masonry (non-industrialized clay bricks and natural stones) and reinforced concrete. Such structures fulfill the function of support (against gravitational and seismic loads) and structural lining. All underground culverts-arch components are constantly subjected to environmental corrosion and to structural loads as well (earthquakes, for example). Mechanisms of degradation of materials are diverse, however, the main source comes from aggressive agents, that is, from gases that emanate from the sewage, such as: hydrogen sulphide, methane and ammonia (Figure 2), associated with oxygen, relative humidity and internal temperature from the sewage system. The evaluated structure has diverse pathologies, classified from common to severe damages which keep it in constant degradation, compromising both its efficiency and durability.

Figure 1. Location and layout of "San Roque Underground culverts-arch" (Mundo, 2019)

It is evident that the lack of inspection and conservation of urban civil infrastructure have provided unfortunate experiences in several structures worldwide, with diverse consequences, for example, undesirable aspects in its structural behavior, and decrease of its service life generated by static or dynamic loads and deterioration by weathering effects; these circumstances have caused the collapse of many civil structures, among others to the underground culverts-arch located in several States of México, some of them have collapsed. For example, in Mexicali, 2004, a section of the underground culverts-arch located at the Nuevo river collapsed due to a structural failure, and in the city of Toluca, the underground culverts-arch located at the Verdiguel River collapsed in 2015 (Mundo *et al*, 2019).

The following are the results of the first exploration carried out in October 2018 by a multidisciplinary group of specialists to determine the current state of deterioration of the structure.

Figure 2. Black water flowing through the "San Roque Underground culverts-arch"

2. VISUAL INSPECTION AND THEORETICAL QUALITATIVE ELEMENTS

The infiltration through cracks, crevices and voids in the underground culverts-arch internal protection (reinforced concrete lining) were observed, causing staining, efflorescence and leaching of calcium hydroxide and other components, which are dispersed over the sides of the concrete surface (Figure 3a). The steel reinforcement of the concrete, both longitudinal and transversal, shows visible corrosion, clearly exposed, with detachment of materials typical of the lining zone and crystallized alkaline leachates, as can be seen on the chainage 0+568 (Figure 3b).

a) b)

Figure 3. Material degradation of the "San Roque underground culverts-arch" structure (Mundo, 2019)

In the reinforced concrete (RC) system, beams and slabs, located at the chainage 0+145, various undesirable structural aspects were observed, such as: a) exposure of longitudinal and transverse steel reinforcement, b) partial longitudinal cracking (Figures 4a) and bursting shown in Figure 4b, highlighted in a blue box. It was observed that, in this last damage zone located in the slab structure, maintenance work had already been carried out (unknown dates of execution). However, it was noted that the construction process used in such maintenance is of low quality, as shown in Figure 4b. Lack of adequate maintenance is evident and therefore, there are notorious material failures such as cracking and detachments in several sections of the RC slab.

a) b)

Figure 4. Material failures: (a). Cracking and (b). Slab bursting

A relevant aspect of the inspection was the identification of a collapsed area of the reinforced concrete structure, located at chainage 0+145, as shown in Figure 5a. In this collapsed section, the severe deterioration due to corrosion of the steel reinforcement and the concrete degradation can be observed. In addition, problems were observed in reinforced concrete beams that have never received maintenance, presenting areas without concrete cover on the bottom side of the element, exposing the steel reinforcement and, therefore, with an active process of generalized corrosion. Moreover, concrete segregation was observed in beams, because the material used as coarse aggregate in the construction process is either from boulder or from river (Figure 5b).

a) b)

Figure 5. a). Slab collapse and b). Areas without concrete cover and with visible concrete segregation in beams of the RC structure

In general, this section of the structure has no conservation and a serious material deterioration process. Various pathologies were observed, both in longitudinal beams, as well as in the reinforced concrete slab (Figure 6), where there are problems of spalling, delamination, segregation, bursting, efflorescence, filtration, humidity, leaching, little or complete lack of the concrete covering for the steel reinforcement and, with light to severe electrochemical corrosion. The latter, is a phenomenon that is due to the action of electrochemical batteries, where metal (steel reinforcement) suffers dissolution in anodic regions, without attacking the cathodic regions, not affecting equally all the metallic surface that are in contact with electrolytic conductivity systems, where the presence of water molecules on the material surface is necessary for this deterioration to occur (Otero, 2001), producing in visible anodic areas, partial or total loss of the bottom longitudinal steel reinforcement (Figure 6, 7a and 7b). In this area, the use of inadequate construction process techniques, lack of quality control of materials and little or no supervision provided is also visible.

Figure 6. General view of slabs and beams with various pathologies

a) b)

Figure 7. a). Severe corrosion with total loss of main steel reinforcement and b). Light corrosion of concrete slab reinforcement

Materials such as brick and stone, joined using mortar, show slight deterioration mainly due to environmental exposure, humidity and internal temperature. The structure built with these materials was observed to be stable and some areas were detected to have stains, eroded areas, soft areas or flabby areas due to excess of humidity in bricks, with efflorescence in the form of crystallized salts (Figure 8). Stains were also visualized by the chemical reaction with water and by bacteria or fungi, including mosses on stones as a result of biological degradation (Figure 9).

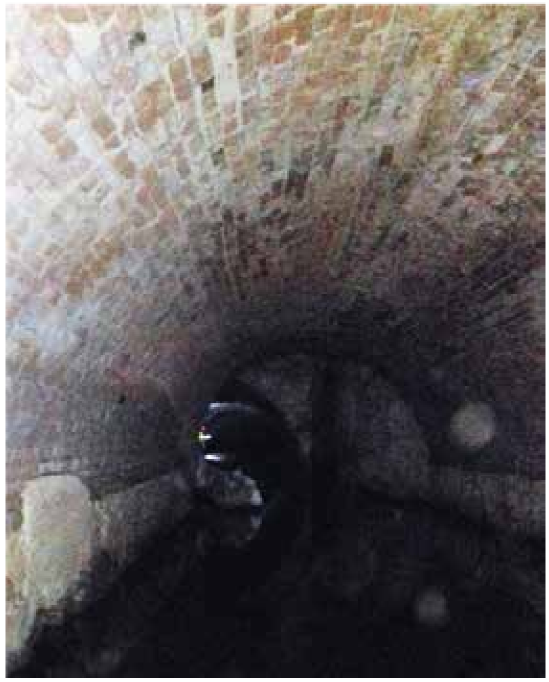

Figure 8. Brick underground culverts-arch´s general view with efflorescence presence (Mundo, 2019)

Figure 9. General view section of the stone underground culverts-arch´s (Tavera, 2018)

Corrosion products exert pressure on the surrounding concrete, causing cracking and detachment of the reinforcing steel cover (spalling), which compromises structural integrity (Castorena *et al*., 2007). This effect obviously has a negative influence on both the structure's durability (steel reinforcement without protection from corrosive atmospheric agents) and its structural behavior.

As commented, all points illustrated above (Figures 3 to 7), could represent important structural risks, as it is known and it has been illustrated (Figures 6 and 7), corrosion can deteriorate steel reinforcement to such a degree that it practically disappears. In such cases, there may be a significant reduction of the flexure and shear strength of individual structural elements. This is due to the fact that when stirrups (and longitudinal steel) corrode, they are no longer useful and the elements' failure mechanism can be modified, instead of having a behavior governed by flexure (assumed at the design stage), as is desirable, premature and sudden shear failures can occur, which is totally undesirable. In addition, in some cases, longitudinal steel rods are much more prone to buckling and the concrete effective area is reduced (Figure 6), affecting its strength. The deformation capacity of the RC members can also be seriously affected by the transverse steel reinforcement degradation, since, in the absence of adequate confinement of the concrete core, deformation capacity (curvature ductility) of transverse sections that make it up can vary significantly from what was originally considered in the design.

Associated to the longitudinal steel reinforcement deterioration, in some cases, rods' corrugations tend to disappear (Figures 5, 6 and 7), so there is also a deterioration in the bond capacity with surrounding concrete (debonding), which could lead to considerable cracking in the presence of extreme actions or even under normal service conditions, as commented by Vidal *et al*. (2007). Bond strength degradation could increase in those sections where, due to the corrosion effects, a lack of effective transverse steel reinforcement for confinement is developed (Fang *et al*., 2004). As indicated in this section, the structural properties of the elements, such as flexural stiffness, shear and flexural strength, can be degraded with the increase of the corrosion levels, due to the steel reinforcement deterioration (caused by the respective induced concrete spalling), since such properties are in function of the amount of longitudinal (the tensile reinforcement ratio, relationship between the tensile and compression reinforcement ratio) and transverse steel reinforcement (stirrups), the resisting effective concrete cross-section area, as well as bond strength between steel and concrete (e.g. Vidal *et al*, 2007, Xia *et al*., 2011, Godínez *et al*., 2019).

3. ELECTROCHEMICAL AND CHEMICAL TESTS *IN SITU*

The selection of the technique to evaluate the corrosion levels was based on both the characteristics of the structure under study and the conditions of the environment where it is located. Therefore, given its speed of application and a very important parameter such as measuring the system's energy from the thermodynamic point of view, the electrochemical technique of corrosion potentials (Ecorr) was used. In this case, a non-destructive test method was used, employing a Copper/Copper Sulphate ($Cu/CuSO_4$) corrosion sensor and a high impedance multimeter with necessary attachments (Figure 10a).

A total of 60 electrochemical readings were taken, one measurement every 50 cm, measured longitudinally on the surface of a 180 cm wide and 700 cm long slab section, as well as on a 75 cm depth and 700 cm long beam (Figure 10b and 10c) with corrosion problems. Measurements of the carbonation front were made on several samples of the collapsed concrete slab, using material remains for the carbonation test, in which an acid-base indicator (phenolphthalein) and a transparent millimetric ruler were used (Figure 11).

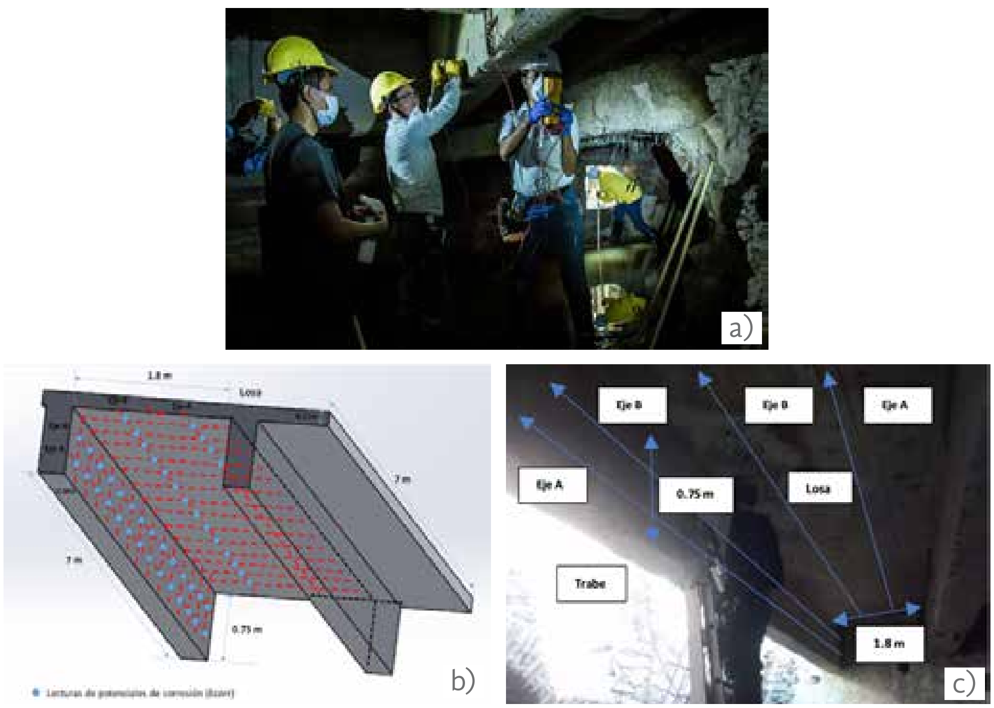

Figure 10. a). In-situ measurements of corrosion potentials (Tavera, 2018), b). Detail of the structure's reading points and c). Measurement axes in slab and beam

Figure 11. In-situ carbonation front measurement in a concrete sample of the slab, using an acid-base indicator solution: phenolphthalein (Tavera, 2018)

4. ANALYSIS AND DISCUSSION

Generally, steel reinforcement embedded in concrete is protected from corrosion due to a two protection characteristics: a concrete cover thickness as a physical barrier and the iron oxide layer (of the order of a couple of nanometers) that forms on its surface, due to high alkalinity of the surrounding concrete, with values higher than 12.6 pH (Peguin *et al.*, 1972). This phenomenon is known as passivation (Fontana, 1986) and prevents steel reinforcement corrosion from spreading further. However, the structure, when acting in its environment, begins to degrade due to various mechanisms that are a function of corrosive elements aggressiveness in the internal environment, soil and water, in which they are in permanent contact (Figure 12).

Figure 12. Underground culverts-arch's internal lining with strong steel corrosion problems and crystallized salts from concrete leaching (Mundo, 2019)

During the inspection, assessment and interpretation criteria for corrosion potentials were applied, from which the in-situ energy flow of the system is measured, as recommended in the *Manual de Inspección, Evaluación y Diagnostico de Corrosión en Estructuras de Hormigón Armado* (Trocónis de Rincón *et al*., 1997) and according to the interpretation of the ASTM C876-91 standard results, as indicated in Table 1.

Table 1

Results' interpretation according to ASTM C876-91

Corrosion potential (Ecorr)	Risk of damage (%)
< -200	10% probability of corrosion
-200 a -350	Certain uncertainty
> -350	90% probability of corrosion

Corrosion potential measurements carried out on the slab and beam that make up the superstructure of the section under evaluation reveal that reinforcement is in active condition. The graph in Figure 13, axis B, corresponding to the slab, shows corrosion potential values that vary from -35 mV to -140 mV, with values ranging from -300 mV to -400 mV detected at the center of the axis. The graph in Figure 13, axis A, of the slab, showed potential values between -20 mV and -140 mV. These values, according to Table 1, indicate that for non-visible reinforcing steel, in general, there is a 10% probability of corrosion for both axes. It should be noted that the most critical values observed in Figure 13 for axes A and B were in the range of some uncertainty and 90% probability of corrosion according to the ASTM C876-91 standard. Therefore, it can be pointed out that the area with high structural problem, where the most negative potentials were computed, is at the center of slab, at 300 cm and 350 cm from its total length. These values coincide with the visible damage observed in the area showing segregations with openings of 10 cm and depths of 1 to 5 cm on average, with corroded exposed steel (Figure 14a).

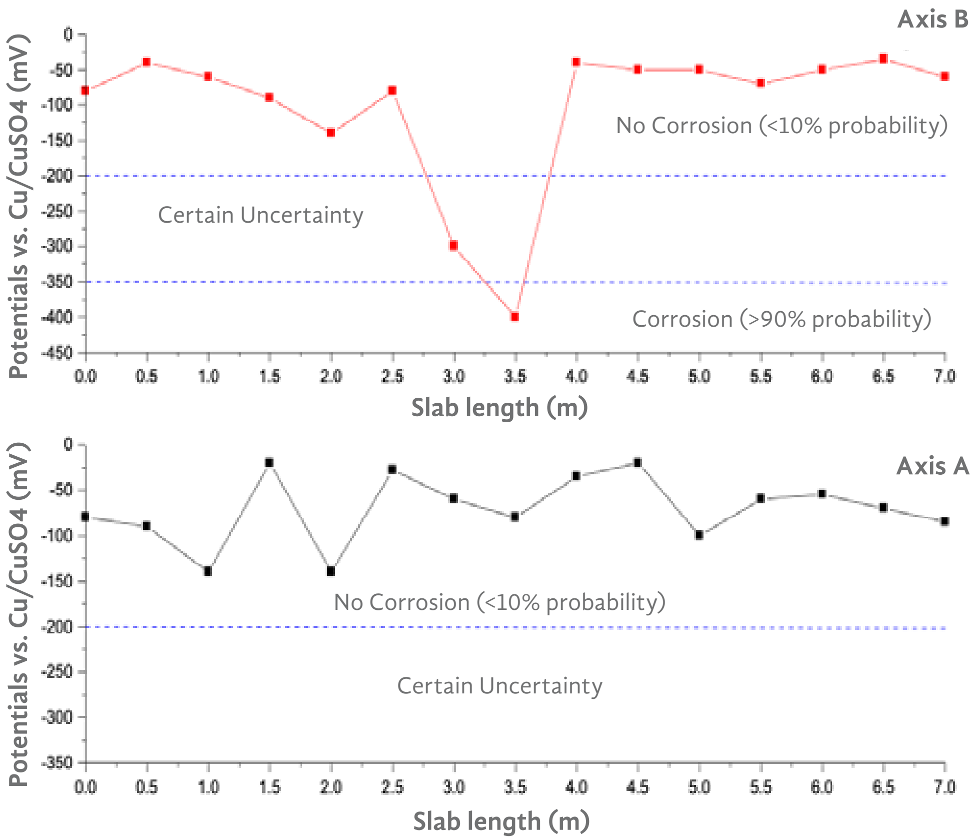

Figure 13. Corrosion potentials (Ecorr) in reinforced concrete slab

a) b)

Figure 14. a). Measurement of deterioration (segregations) in slab and b). Measurement of beam's segregations with digital vernier "Mitutoyo" and transparent millimetric ruler

From the A axis of Figure 15, corresponding to the beam, potential values that vary from -45 mV to -336 mV were observed. In graphic 15, in axis B of the beam, values between -75 mV and -330 mV were observed. These values, according to Table 1, indicate for non-visible steel reinforcement have a 10% risk of corrosion damage and some uncertainty for both axes. It should be noted that the most negative potentials were in the range of some uncertainty according to the standard. Therefore, it can be pointed out that the higher structural problem, which presents the most negative potentials, is located at 450 and 600 cm from its total length. These values match with the visible damage observed in the beam area, which shows segregations with openings of 15 cm and depths of 2.3 to 5 cm, with exposed corroded steel (Figure 14b).

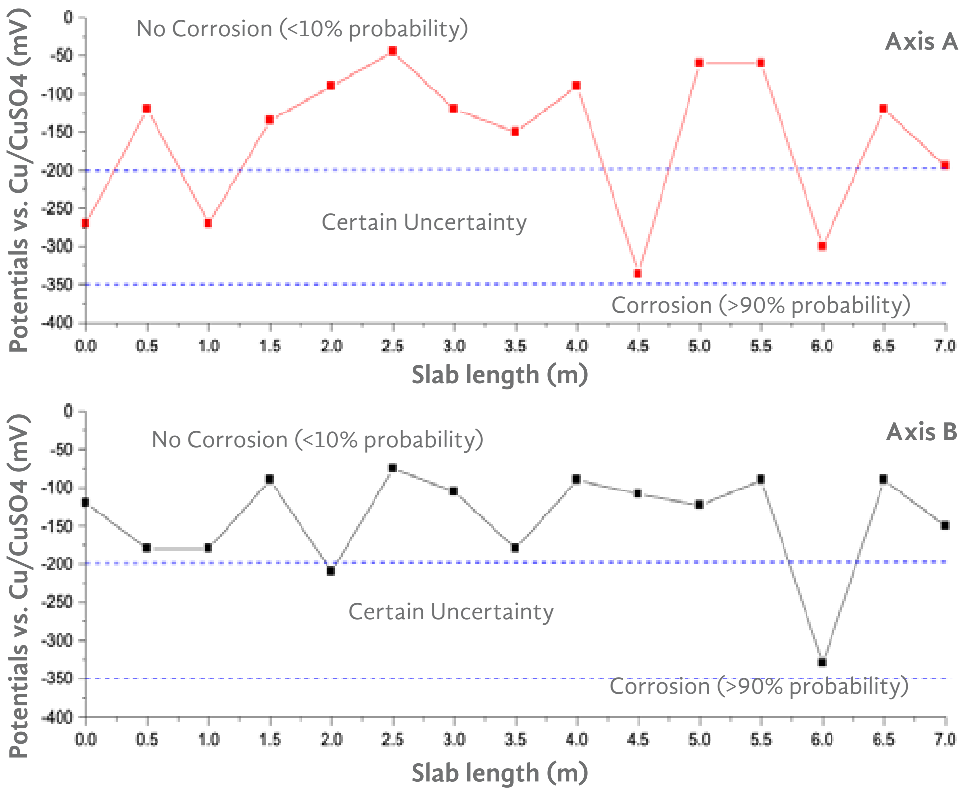

Figure 15. Corrosion potentials (Ecorr) in reinforced concrete beam

It is important to mention that remains of totally corroded steel were found inside concrete segregation voids, in the form of pores and voids, detecting punctual signs even <-500 mV vs Cu/CuSO4 for adjacent areas, detected with severe corrosion, not recorded in previous graphs. This active tendency of reinforcing steel in the steel-concrete system, once the corrosion driving force starts, this material will have a tendency towards stable equilibrium, until this parameter has reached a minimum value in the system (González, 1989), in other words, total steel degradation.

On the other hand, carbonation is a process in which carbon dioxide (CO_2) from the atmosphere reacts with the alkaline components of the concrete's aqueous phase, lowering its pH and resulting in neutralization of all material. From data obtained through the concrete's phenolphthalein test, an advanced depth of carbonate front was found (2 cm), this value, even in certain degraded parts, is greater than the coating's free zone. Concrete's pathology, together with alkalinity loss, promotes the appearance of damage such as fine cracks and flabby areas, which end up in delamination near the reinforcement steel level with light, medium, strong and severe category (Carmona, 2003). This was corroborated by material detachment over 25% of the slab and beams surface analyzed *in situ*. Another consequence is the generalized reinforcing steel's depassivation, forming electrochemical cells due to chloride diffusion and sulfate ions, which increase their mobility in carbonated concrete. Sewage aggressive agents and its vapors, as well as the atmosphere of the drainage system, in addition to the alkaline reserve leaching, are the accelerating factors that keep the structure in constant degradation.

There are other parameters that promote steel-concrete system pathologies, such as temperature, which plays a double role in deterioration processes. Its increase helps molecules' mobility, facilitating transport of substances, among them aggressive ones, and its decrease in condensation of local humidity in materials that favor their deterioration. Environmental humidity promotes corrosion in neutral and alkaline environments, intervening in cathodic processes of oxygen reduction, as well as favoring ions mobility through electrolyte (concrete). Differences in oxygen concentration in different areas around reinforcing steel due to cracks presence, porosity and surface damage, accelerate differential aeration piles formation, triggering steel corrosion. This mechanism is common in carbonated concrete.

The concrete patch observed in Figure 4b (blue square) corresponds to blowout damage, generally caused by reactive aggregates and cement that are high in alkalis, or in its case, by aggregates that expands when is in constant contact with water or humidity. In this case, it is a severe burst that has been repaired, since the damage diameter is greater than 5 cm and depth greater than 2.5 cm (Carmona, 2003).

Cracks located on the analyzed slab lower surface, in chainage 0+145, are structural damage caused by dead and live loads, ranging from strong to severe cracking, with cracks from 0.6 mm and larger than 1 mm wide.

It should be clarified that during the development of this research, the City Council of Tuxtla Gutierrez has undertaken some maintenance work on the underground culverts-arch, focusing exclusively on repairing sinkholes; however, procedures and techniques used are not the most desirable (Mundo *et al*., 2019a), from a technical point of view.

It is important to emphasize that it is indispensable to obtain data of the temperature, relative humidity, gas emissions, aggressive ions, as well as mechanical tests for concrete, stone and brick materials in order to achieve a more thorough inspection. It is also important to carry out a study of the contaminants in the sewage. Finally, it would be highly recommendable, in the reinforced concrete structure case, located at chainage 0+145, to perform reinforcing steel corrosion kinetics by means of electrochemical techniques, as well as to perform chemical tests on concrete, to analyze the penetration of aggressive agents such as chloride and sulfate ions.

CONCLUSIONS

It has been shown and discussed the impact of the material degradation in the sewage infrastructure, mainly of an internal reinforced concrete (RC) element, which crosses the San Roque underground culverts-arch in chainage 0+145. Based on visual inspection and results from carried out tests, the following conclusions are made:

The San Roque underground culverts-arch structure lacks of constant and preventive maintenance. For the RC slabs and beams that transversely cross the underground culverts-arch in chainage 0+145, physicochemical damages are strong and severe and, visible in its diverse pathologies.

The corrosion of the steel reinforcement in the structure is from electrochemical nature and is due to constant action of humidity and advanced carbonation, together with aggressive agents emanating from the sewage.

Based on measurement of potentials in the evaluated reinforced concrete slab and beam, it was observed that the most negative voltage recorded coincide with the most deteriorated areas and the risk of damage to the reinforcing steel, according to Table 1, corresponds to a 10% to 90% probability of very high corrosion in the adjacent anodic areas with voltages below -350 mV.

Concrete's *in-situ* carbonation test, using phenolphthalein, shows advanced depth of the front of carbonation, 2 cm in average, enough to reach the main steel of the beams and slab. This degradation by carbonation in the elements is accentuated by the small or total lack of concrete cover observed, which was measured in areas showing segregations for both elements that range from 1 to 5 cm deep and openings between 10 and 15 cm in average, presenting exposed steels rods without concrete cover. These damages are mainly due to the low material quality control and lack of supervision during its construction.

Brick and natural stone masonry sections are stable, with samples of saltpeter and stains due to fungi, so the risk of damage is low.

Among the most evident structural consequences that may occur (or already exist) in the analyzed structure (chainage 0+145): local and global load capacity problems, significant bond strength losses between steel and surrounded concrete, modification of failure mechanism (from ductile to brittle), loss of deformation capacity (local and global) and susceptibility to buckling of longitudinal steel reinforcement.

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USED FORMULAS, ABBREVIATIONS, ACRONYMS

Cu/CuSO4	Copper/Copper Sulphate
CO2	Carbon dioxide
Ecorr	Corrosion Potentials
mV	Millivolt
pH	Unit of measure which describes the degree of acidity or alkalinity of a solution
in-situ	On-site
cm	Centimeters