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Non-Destructive Testing of Concrete Materials from Piers: Evaluating Durability Through a Case Study

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Abstract: Concrete is currently the most used construction material, mainly due to its mechanical strength, chemical stability, and low cost. This material is affected by wear processes caused by the environment, which lead to a reduction in the useful life of the infrastructure in the long term. These wear processes can cause cracks, corrosion of reinforcing steel, loss of load capacity, and loss of concrete section, among other problems. Considering the above, it is necessary to carry out durability studies on concrete to determine the integrity conditions in which the infrastructure is found, the reasons for its deterioration, the environmental factors that affect it, and its useful life under these conditions, and develop restoration or protection plans. Generally, the durability studies include non-destructive testing such as ultrasonic pulse velocity, electrical resistivity, porosity measurement, and capillary absorption rate. These techniques make it possible to characterize the concrete and obtain information such as the total volume of pores, susceptibility to corrosion of the reinforcing steel, decrease in mechanical resistance, cracks, presence of humidity, and aggressive ions inside the concrete. In this work, two durability studies are presented with non-destructive tests carried out on active piers that are 20 and 40 years old. These are located in coastal areas in southern Mexico on the Gulf of Mexico side, with 80% average annual relative humidity, temperatures above 33 °C on average, high concentrations of salts, load handling, vibrations, flora and fauna typical of the marine ecosystem, etc. The results obtained reveal important information about the current state of the piers and the damage caused by the environment over time. This information allowed us to make decisions on preventive actions and develop appropriate and specific restoration projects for each pier.

Keywords: case study; concrete; damage; durability; integrity evaluation; non-destructive testing; piers

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1. Introduction

Defects that reduce the service life of concrete structures can be divided into primary and secondary defects [1]. Primary defects are those attributed to human error, such as poor mix design or inadequate material selection. On the other hand, secondary defects are caused by a gradual deterioration of concrete properties because of the physical, chemical, and biological effects of the environment.

Generally, aggressive environments for concrete are characterized by the presence of factors such as sudden temperature changes, which represent damage to the mechanical and microstructural properties of the concrete [2]. Abundant presence of aggressive ions, such as Cl^-, SO_4^{2-}, and Mg^{2+}, are capable of initiating corrosion of the reinforcing steel and producing expansive oxides that cause fractures in the concrete [3–5]. Another aggressive environmental factor for concrete is a high concentration of CO_2 in the atmosphere, which can penetrate the concrete pores, react with its hydrated components to form calcium carbonate, and reduce the alkalinity of the concrete [6].

The nature of these factors does not allow for classifying the concrete degradation process into well-defined categories due to the difficulty of differentiating the degradation processes that a structure exposed to the environment undergoes, since these physical and chemical processes are related, occur simultaneously, and can compete with each other [7]. This makes it necessary to design concrete with durability criteria; when concrete is designed with durability criteria, its structure, quality, and service capacity are preserved despite exposure to the elements over time [7]. The durability of concrete can be defined as the ability of the material to resist deterioration when subjected to abrasion, physicochemical attacks, and various environmental conditions during its use [8,9].

It is possible to evaluate the durability and integrity of concrete with non-destructive testing (NDT), which, together, provides a complete overview of the current state of the infrastructure and includes tests such as the following: total porosity, which allows for measuring the volume of pores in the concrete and is related to the rate of penetration of aggressive substances [10]; ultrasonic pulse velocity, which is used to detect internal cracking and defects that can be caused by aggressive chemical environments, freezing, and thawing [11]; capillary absorption, which allows for determining the susceptibility of an unsaturated concrete to the penetration of water [12]; and electrical resistivity, which can be used as a parameter to predict properties such as microstructure, porosity, composition, contamination, and alteration caused by the environment [13,14].

In this work, non-destructive durability tests (total porosity, ultrasonic pulse velocity, capillary absorption, and electrical resistivity) were carried out on concrete samples extracted from two piers that are currently in service. These piers are between 20 and 40 years old and are exposed to an environment with an average relative humidity greater than 80%, average temperatures of 33 °C, high concentrations of Cl^{-}, load handling, and vibrations due to the pier's own use and the flora and fauna present in the environment.

The information contained in this work is important because it reveals how the external environment damages construction elements fabricated with materials designed to "resist" this environment, which is different from cementitious mixtures that are manufactured in laboratories and then exposed to simulated environments.

2. Methodology

For the study performed in this article, the following methodology was carried out (see Figure 1):

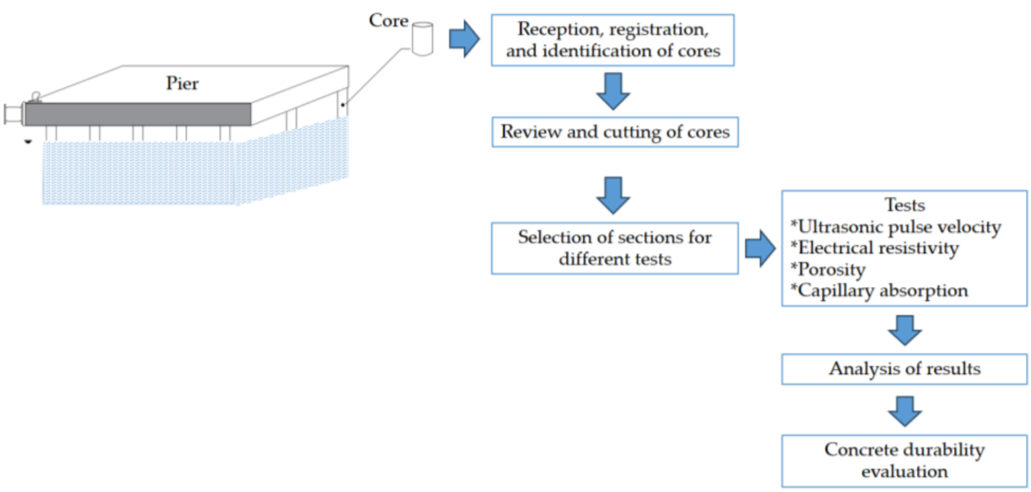

Figure 1. Schematic diagram of the methodology followed in this study.

1. Obtaining concrete cores from the pier to be evaluated.
2. Reception, registration, and identification of the concrete cores.

3. Review and cutting of concrete cores.
4. Selection of cores' sections for the different tests.
5. Ultrasonic pulse velocity tests.
6. Electrical resistivity tests.
7. Porosity tests.
8. Capillary absorption tests.
9. Analysis of results.
10. Concrete durability evaluation.

First, the respective cores are obtained from the pier to be assessed and all of them are identified and registered in the corresponding record sheets. After that, the concrete cores must be visually inspected and cut with adequate sizes and shapes according to the standards of the tests that will be carried out. Subsequently, the tests (total porosity, ultrasonic pulse velocity, capillary absorption, and electrical resistivity) are performed in the corresponding defined sections of the cores. Lastly, the results are analyzed, and the concrete durability is evaluated according to the standards of the different tests.

The different non-destructive experimental tests are described below.

2.1. Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity (UPV) is the relationship between the travel distance, through concrete, of an ultrasonic wave and the time it takes to travel [15,16]. It is a non-destructive test whose main objective is to verify the homogeneity (uniformity and relative quality) of the concrete, which allows for monitoring of the variations in the properties of the concrete over time [15,17].

The UPV test consists of measuring the time it takes for an ultrasonic pulse to travel the distance between an emitter transducer and a receiver transducer, both coupled to the specimen under study [15]. The emitter electroacoustic transducer is responsible for generating longitudinal vibrations, while the receiver is responsible for receiving the signal from the emitter after traveling a distance (L), and, finally, by means of an electronic circuit, the propagation time of the impulse through the material is measured [15,18].

Thus, the pulse speed (V) is calculated by dividing the length (L) that the wave travels by the time (t) it takes to travel it, as represented in Equation (1).

$$V = \frac{L}{t} \tag{1}$$

On the other hand, the criteria to evaluate the UPV results are presented in Table 1; these are based on Mexican standard NMX-C-275-ONNCCE-2019 [19] and ASTM parameters [18]. Table 1 can be applied to saturated concrete such as the cores that were tested; in this way, the propagation velocity of the ultrasonic wave through the concrete core is related to the quality of the concrete in terms of material homogeneity and the curing process.

Table 1. Classification of concrete quality using UPV.

Propagation Velocity (m/s)	Concrete Qualitative Classification
≤3000	Doubtful
3000 to 3500	Medium
3500 to 4500	Good
≥4500	Excellent

The ultrasonic instrument used was the Controls© UPV meter, model E48 (fabricated by Control System Labs, New York, NY, USA), which has a frequency range from 24 kHz to 150 kHz with a precision of 0.1 µs. In Figure 2, pictures from UPV tests performed for this research can be observed.

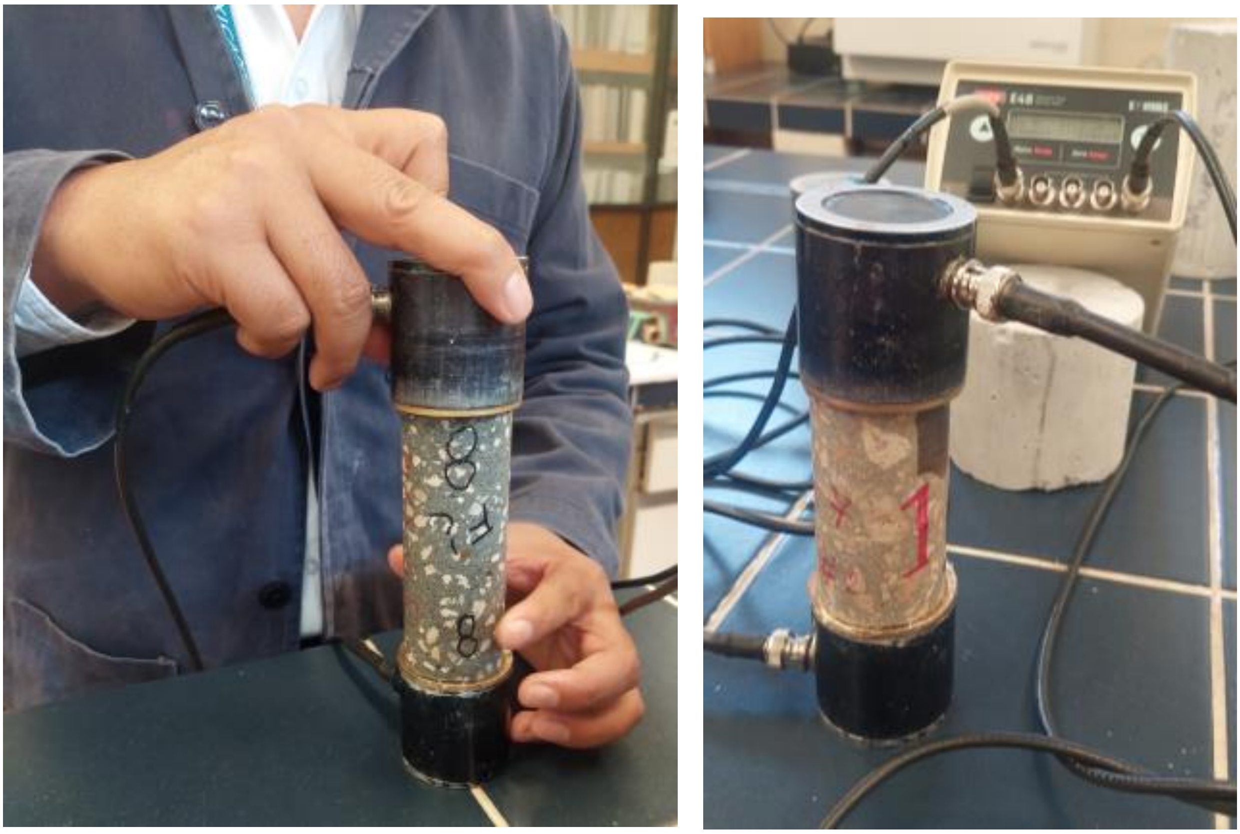

Figure 2. Representative pictures of the UPV measurement of unsaturated concrete cores.

2.2. Electrical Resistivity Test

Electrical resistivity is the resistance that materials present to the passage of electric current and its unit of measurement is Ω·cm or Ω·m [20]. Therefore, electrical resistivity corresponds to the reciprocal of electrical conductivity and is a characteristic property of each material.

Resistivity is an indicator of the setting process and mechanical resistance, the degree of saturation of the concrete, and, therefore, the degree of curing and the impermeability or resistance to the entry of aggressive substances into the concrete [15].

For laboratory tests, resistivity is calculated using the real resistivity method. It begins with the preparation of the specimens to be evaluated; once ready, they are assembled on a flat, non-electrically conductive surface. At the bases of the specimen, wet sponges are placed, the specimens are pressed with stainless steel or copper plates that cover at least the cross-sectional area of the specimen, and an overweight is placed on the upper surface to fix the core and prevent loss of electrical contact. Once the specimen is fixed, the equipment is connected to the stainless steel plates at the ends and the measuring equipment (resistometer) begins to operate, acquiring data. Finally, the calculation of the electrical resistivity (ER) is carried out by means of Equation (2), where E corresponds with the voltage response recorded and I with the electric current applied:

$$ER = \frac{E}{I} \tag{2}$$

Figure 3 shows an example of an electrical resistivity test using Nilsson© equipment (fabricated by M.C. Miller Company, Sebastian, FL, USA).

Electrical resistivity tests were carried out in accordance with ASTM G57-20 [21] and Mexican standard NMX-C-514-ONNCCE-2019 [22]. The evaluation criteria of the results obtained from this method are presented in Tables 2 and 3.

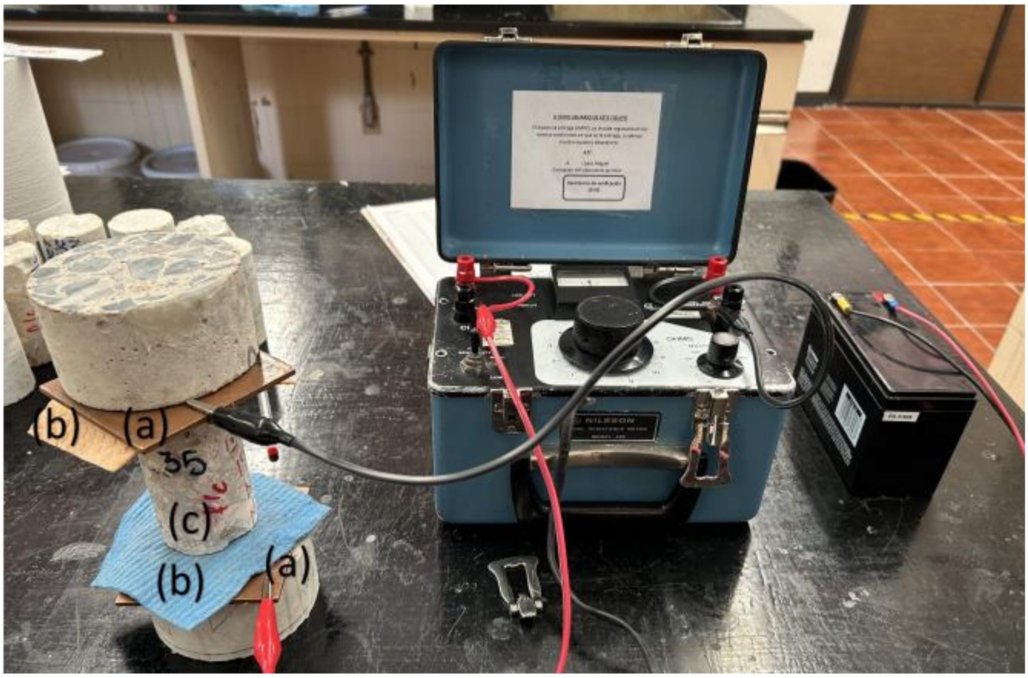

Figure 3. Electrical resistivity measurements performed on concrete cylinders: (**a**) stainless steel/copper plate, (**b**) wet sponge, and (**c**) concrete core.

Table 2. Electrical resistivity criteria according to Durar Network [23].

Resistivity Value (kΩ·cm)	Criterion
>200	Low risk of corrosion
200 > 10	Moderate risk of corrosion
<10	High risk of corrosion

Table 3. Electrical resistivity criteria according to Mexican regulations [24].

Resistivity Value (kΩ·cm)	Qualitative Classification
>100 to 200	Concrete is very dense, so its interconnected porosity is extremely low, as is the transport of aggressive agents to the reinforcing steel. The corrosion rates of the steel itself are very low, regardless of the chloride content or the carbonation level. There is no distinction between steel in an active or passive state.
50 to 100	Concrete has a low interconnected porosity, making it difficult to transport aggressive agents to the reinforcing steel. The corrosion rates of the steel itself are low.
10 to 50	Concrete has a considerable interconnected porosity, allowing the transport of aggressive agents to the reinforcing steel rapidly. The corrosion rates of the steel itself are moderate or high in carbonated or chloride concretes.
<10	Concrete has excessive interconnected porosity, allowing the transport of aggressive agents to the reinforcing steel in an extremely rapid way. The corrosion rates of the steel itself are very high in carbonated or chloride concretes. Resistivity is not the parameter that controls the corrosion process. The corrosion rate value obtained with the NMX-C-501-ONNCCE reflects the upper limit of the corrosion rate of concrete for a given chloride content or carbonation level.

2.3. Porosity Test

Porosity is defined as the empty spaces left in the concrete mass, as a consequence of the evaporation of excess water from mixing and air trapped during handling. The methodology followed to determine the percentage of total porosity is based on ASTM C642-21 [25] and Mexican standard NMX-C-504-ONNCCE-2015 [26], which establishes that the total porosity of the concrete cores must be evaluated according to Equation (3), as is shown next:

$$\% \; Total \; porosity = \frac{W_{sat} - W_{105^\circ\mathrm{C}}}{W_{sat} - W_{sub}} \quad (3)$$

where W_{sat}, $W_{105^\circ\mathrm{C}}$, and W_{sub} are related to the weights of the mass superficially dried after immersion, dry mass, and submerged mass, respectively [23,25]. On the other hand, the evaluation criterion used for this study is presented in Table 4, where the concrete characteristics are defined as a function of the total porosity percentage.

Table 4. Evaluation criteria for total porosity measurements according to Durar Network [23] and Neville et al. [15].

Total Porosity (%)	Concrete Characteristics
≤10	Good quality and compactness
10 to 15	Moderate quality
>15	Inadequate durability

Finally, a picture showing the determination of the saturated and submerged weight of a concrete core by using a hydrostatic scale is shown in Figure 4.

Figure 4. Determination of saturated and submerged weight by using a hydrostatic scale.

2.4. Capillary Absorption Test

Capillary absorption is considered the mass of water per unit of area that can be absorbed in the capillary pores when the concrete is in contact with liquid water. This represents the effective or accessible porosity to water and therefore to the aggressive ions that are present in the environment [12].

In other words, absorption (I) is the change in mass (Δm) in units of g divided by the product of the cross-sectional area of the core (a) in mm^2 and the water density (p) in g/mm^3, thus giving the units in mm, as represented in Equation (4).

$$I = \frac{\Delta m}{a \; p} \quad (4)$$

Likewise, other parameters that are useful to complement this test and obtain more information about the core are capillary absorption coefficient (K), resistance to water penetration (m), and capillary sorptivity (s), whose equations are presented, respectively, below:

$$K = \frac{W_t - W_o}{A\sqrt{t}} \tag{5}$$

$$m = \frac{t}{z^2} \tag{6}$$

$$s = \frac{1}{\sqrt{m}} \tag{7}$$

where W_t represents the weight of the mass at a given test time, W_o the initial weight of the core before starting the capillary absorption process, A the area of the core, t the test time of the core, and z the height that the water reaches through capillary absorption in the core.

In this way, the durability sorptivity value specifications used in this article are shown in Table 5.

Table 5. Durability sorptivity value specifications according to the guide describing the use of durability indexes for achieving durability in concrete structures [23].

Environments	Sorptivity (mm/h$^{1/2}$)
Harsh environment	≤3
Less severe environment	Up to 6

Finally, Figure 5 shows a picture of different specimens during capillary absorption tests.

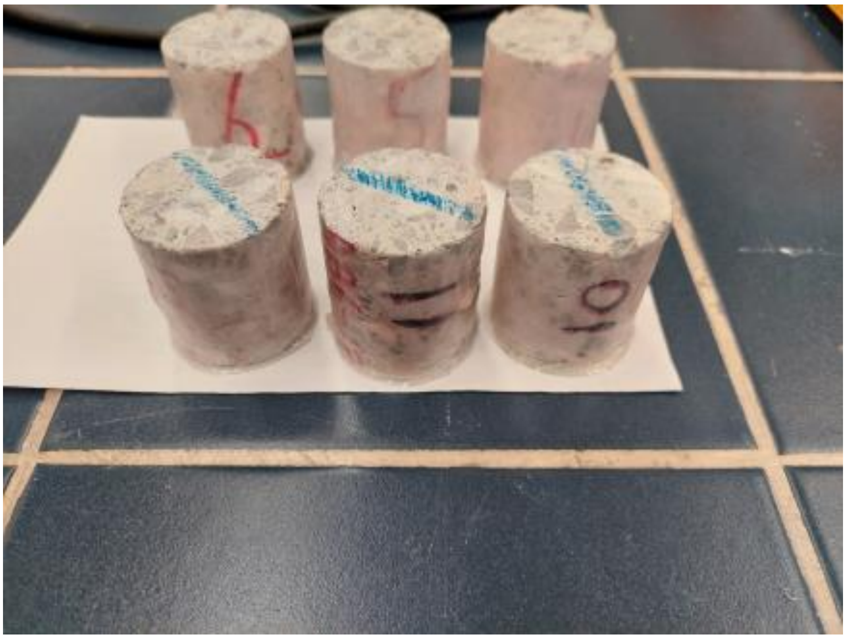

Figure 5. Preparation of specimens for capillary absorption.

3. Results

The results obtained are presented in groups according to the type of concrete element evaluated, i.e., the average of the results obtained for piles, t-beams, and slabs. The results are obtained from two piers of different ages and applications. M1C is a pier for load transport with an age of 20 years; its dimensions are 300 m in length and 11.40 m in width. M2T is for tourism; its age is 40 years, and it has 251 m of length and 20 m of width. Both of them have 180 piles (see Figure 6).

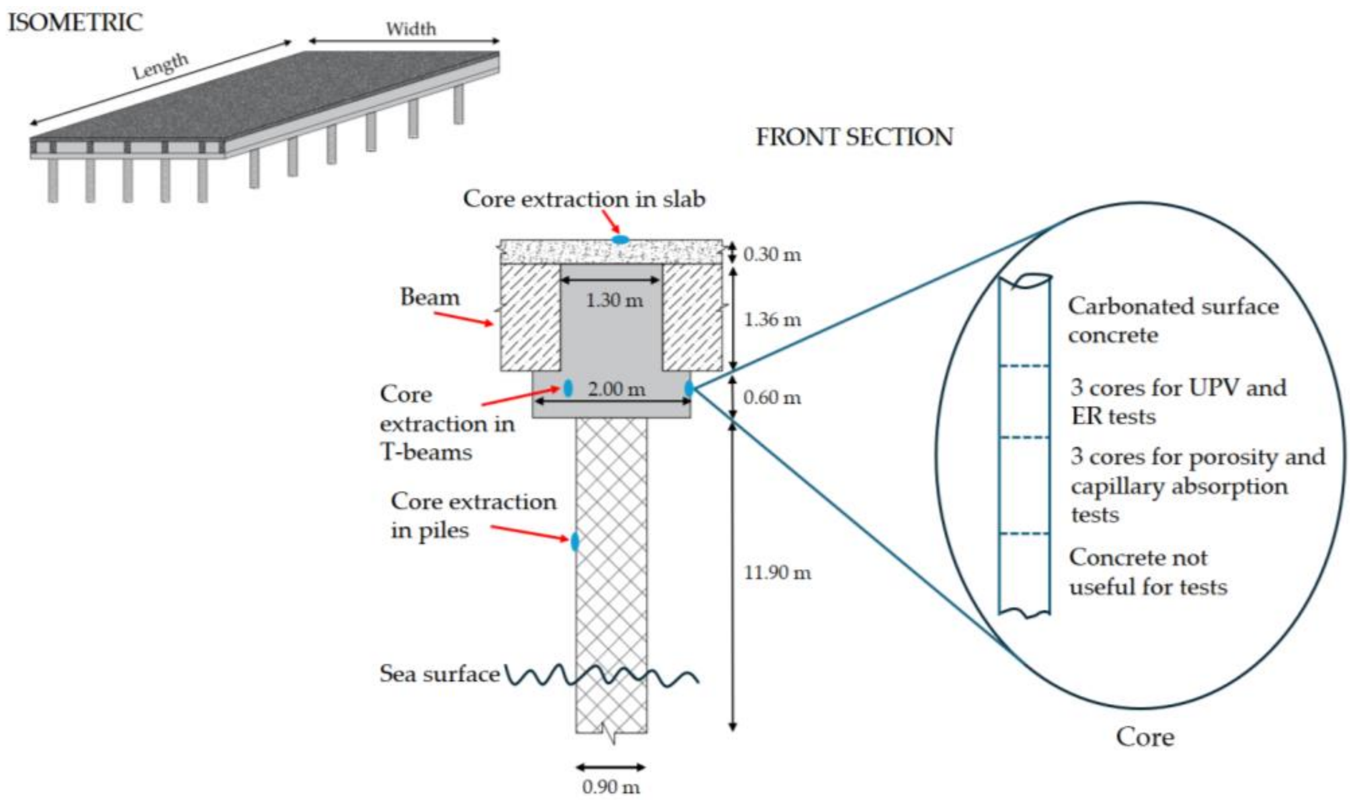

Figure 6. Schematic layout showing elements, general dimensions, and sampling locations for the piers.

Considering Figure 6, the main elements of the structures were selected: piles, T-beams, and slabs. From these elements, concrete cores were placed in the front area of the pier (area of greatest exposure to inclement weather). Cores of different dimensions of approximately 5 cm × 30 cm were extracted; these were sectioned into 5 cm × 10 cm cores for VPU and resistivity tests, and 5 cm × 3 cm cores for the total porosity and capillary absorption percentage tests. A total of 27 items were obtained for the mentioned tests. In order to obtain repeatability of results, all tests were performed in triplicate and only the average values are presented.

The number of samples is defined by the engineering department of the pier, as they limit the extraction of samples to ensure the safety and operation of the pier; in this way, cores of sufficient size were extracted and taken at least in triplicate for each test.

NDT can be applied onsite; however, the tests carried out, such as resistivity, porosity, and sorptivity, require taking samples, which are representative of the structure. Moreover, it is worth mentioning that resistivity and UPV tests could present interference due to the existence of steel in these structures. Therefore, it is advisable to take specimens and perform laboratory tests.

3.1. *Ultrasonic Pulse Velocity*

The UPV results were calculated according to Equation 1 and evaluated according to the criteria shown in Table 1.

These results obtained on saturated concrete samples (Figure 7) reveal a good concrete quality for the three types of elements (piles, t-beams, and slabs) of M1C. In the case of the tourist pier, the results reveal medium quality for the slab and good quality for the piles and t-beams. These results indicate good concrete quality in spite of the difference in age and application of these structures. However, the slab of the tourist pier is the one with the lowest quality; this can clearly be attributed to its use, since fishermen also use the pier, and the slab has more contact with seawater, and therefore, deterioration is generated.

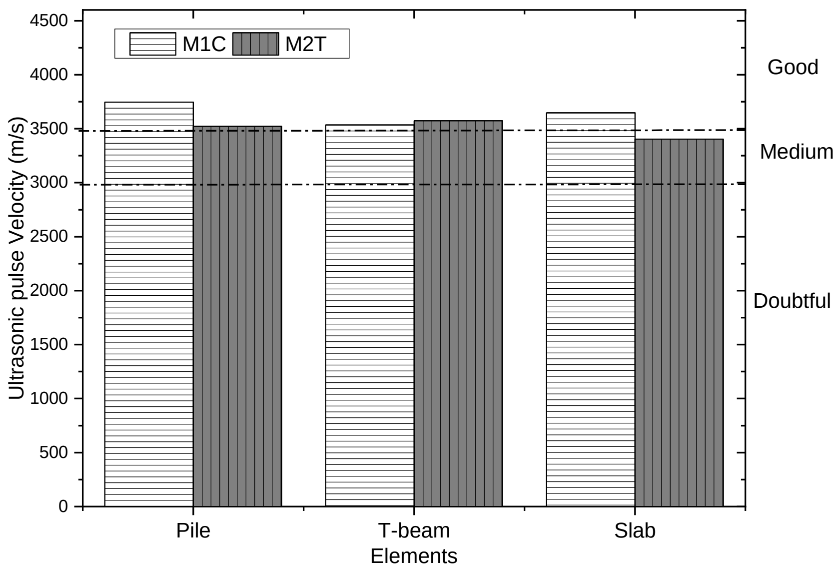

Figure 7. Ultrasonic pulse velocity results by element type.

The UPV results indicate that the concrete quality is good in terms of density, homogeneity, and uniformity. That means that the concrete core evaluated does not contain cracks and that it is homogeneous in terms of the materials of the hardened mix. This is because the VPU technique allows for knowing how the setting process was carried out and if this material has any discontinuity or cracking (according to the ASTM standard), whereas for cores contaminated with Cl^-, the resistivity is lower. On the other hand, Table 3 refers to the physical properties of hardened concrete, related to porosity and interconnectivity.

3.2. Electrical Resistivity

The ER results were calculated by applying Equation (2) and evaluated by considering the criteria indicated in Table 2. These ER values indicate that according to the concrete quality criteria (dotted lines marked on the plot in Figure 8), the quality of the concrete in both concrete structures is of excessive interconnected porosity, so the risk of steel corrosion in this concrete is very high (as indicated in Table 2). It should be noted that for M1C, resistivity values slightly higher than those of M2T are observed; this is attributed to the difference in age between these piers.

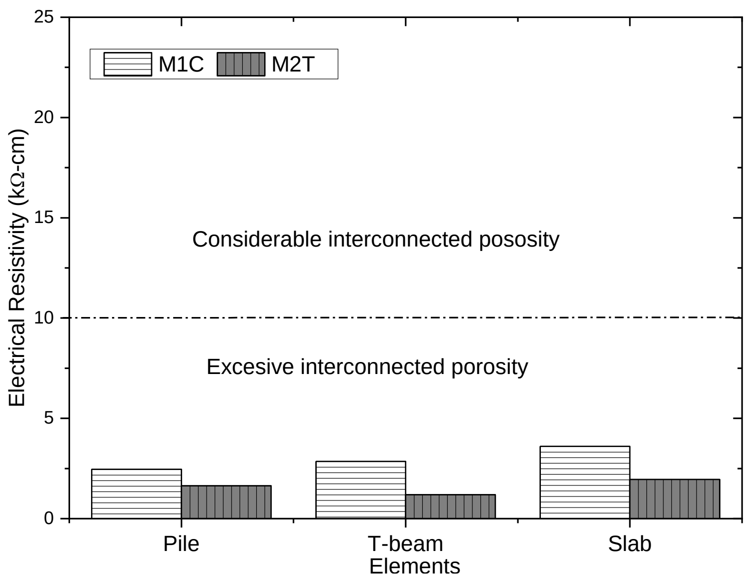

Figure 8. Electrical resistivity results of concrete elements.

The concrete in both structures is of very poor quality; however, over the years, this has worsened as a result of salts' penetration into the pores of the concrete, making it a more conductive and corrosive environment for the steel embedded in it. Smith et al. [27] report values of 8 kΩ·cm and 12 kΩ·cm as zones, in which the likelihood of steel corrosion is medium to high, and they consider greater than 12 kΩ·cm as a zone in which the likelihood of corrosion exists.

3.3. Total Porosity

The results of total porosity in the different concrete elements are shown in Figure 9. In both piers, an inadequate durability of the concrete is observed, according to the criteria presented in Table 4.

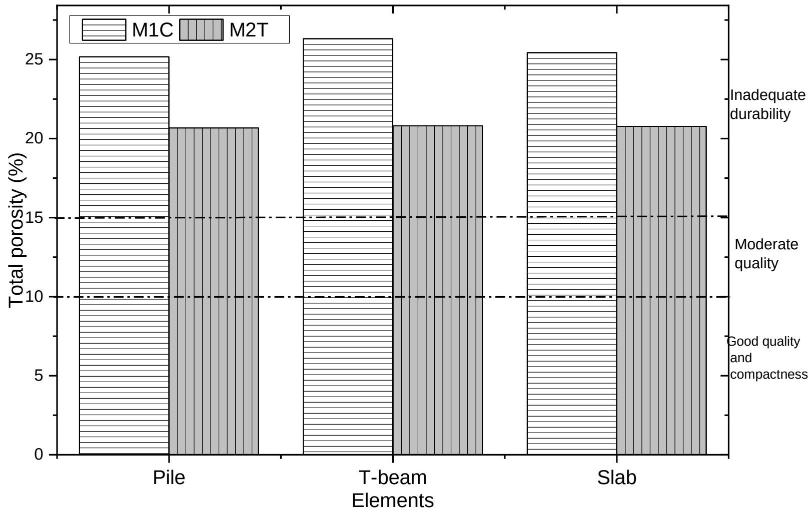

Figure 9. Results of total porosity in concrete elements.

3.4. Capillary Absorption

Figures 10 and 11 show the curves corresponding to the results obtained in the capillary absorption test. The y-axis is related to the amount of water absorbed per unit area of the sample, whereas the x-axis shows the square root of the elapsed time. The table with the values of capillary absorption rates and linear correlation coefficients is also presented (Table 6).

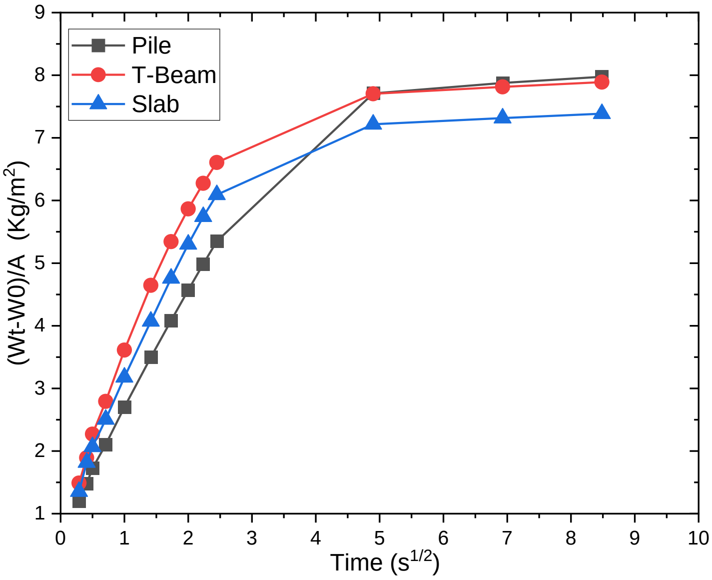

Figure 10. Water capillary absorption curves obtained for M1C for the weight changes in the cores versus time.

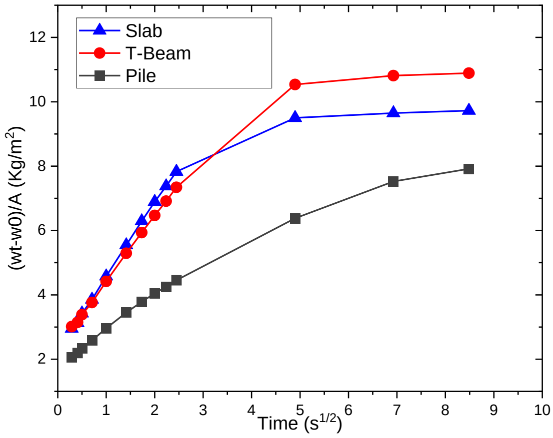

Figure 11. Water capillary absorption curves obtained for M2T for the weight changes in the cores versus time.

Table 6. Average values obtained for water penetration resistance (m), absorption coefficients (K), and sorptivity (s) from the capillary water absorption test.

ID	Resistance to Water Penetration, m (s/m^2)	Capillary Absorption Coefficient, K (kg/m^2 $\times$ s$^{1/2}$)	Sorptivity, s (mm/h$^{1/2}$)	Linear Correlation Coefficients, r
		M1C		
Pile	1.99×10^8	0.014	5.6	0.99
T-Beam	3.31×10^8	0.012	6.0	0.99
Slab	4.01×10^8	0.012	5.4	0.99
		M2T		
Pile	1.50×10^8	0.02	4.2	0.99
T-Beam	2.15×10^8	0.02	3.3	0.99
Slab	1.45×10^8	0.02	3.0	0.99

The Fagerlund kinetic parameters [28] describing the capillary absorption and sorptivity of the main spring elements are presented in Table 6. The linear correlation coefficient is calculated with a linear regression analysis using the least squares method applied to each specimen at initial uptake (1 to 360 min) and at secondary uptake from 1 to 7 days. Each specimen should follow a linear relationship, and the correlation coefficient r should be greater than 98. This is calculated at the points on the plot of mass increase per m^2 vs. square root of time.

Regarding capillary sorption, the recommendation for coating thicknesses of 30 mm of concrete in severe environments is $s \leq 3\text{mm/h}^{1/2}$, whereas in less severe environments, it can be up to 6 mm/h$^{1/2}$. The capillary sorption values obtained in the tests reveal that the concrete is not suitable for these conditions or severe environments.

4. Discussion

A probability-based durability scheme must be used to consider all variabilities. Most of the durability problems are due to deficient quality control and inconvenient situations generated during concrete construction. Therefore, the construction quality as well as the variability have to be necessarily taken into account before designing a more detailed scheme for increasing durability control. Thus, during concrete construction, it is very important to carry out adequate quality control of the concrete performance, including the respective documentation of the construction quality obtained and compared with the specified durability [29].

In terms of long-time durability, the required level of concrete quality is obtained by ensuring the limiting values of durability indicators of concrete at a particular age. The performance-based durability indicator values can be set for a particular mix, based on the durability index values of the laboratory-prepared specimens. Testing whether the site concrete has reached the desired specification value helps to ensure the quality of the finished product [30].

4.1. Discussion for Ultrasonic Pulse Velocity

The results of the UPV tests, presented in Figure 7, were obtained from cores that were saturated with water; under this condition, it is assumed that all the pores, cracks, and internal defects of the concrete are filled with water, which generates a quick transmission of the ultrasonic pulse. It is worth mentioning that the speed of the pulse through the concrete is strongly associated with the compactness or health of the concrete; in this case, it indicates that the concrete samples tested do not contain cracks or voids that affect the concrete performance.

According to the criteria established in the Mexican standard NMX-C-275-ONNCCE-2019 and ASTM C 597 (see Table 1), the cores indicate medium-quality concrete for the slabs and good quality for piles and beams. However, it can be observed that the slabs from M2T show values associated with concrete with poorer quality or more defects. Nevertheless, there is a controversy between performing the UPV test on specimens saturated with water or dry conditions, as described by the Mexican standard and the report Fire Technology SP Report 2011:19 [31], respectively.

The durability index is a function of the concrete quality in terms of its curing period and material homogeneity (determined by VPU), which determines its physical properties and its resistance to the penetration of gases, liquids, and ions through its surface. This is very important because sorptivity, permeability, and conductivity are determined with relatively simple tests, which allow for predicting the useful life of the infrastructure, keeping in mind that capillary pores are important due to the fact that they allow the entry of external agents.

On the other hand, these results seem to contradict the data obtained from the electrical resistivity, total porosity (total volume of voids), and capillary adsorption tests. However, the total porosity results indicate that the quality of the concrete is poor, suggesting that the placement of the concrete as well as its curing process had to be performed with more care, as discussed below.

4.2. Discussion for Electrical Resistivity

According to Mexican standard NMX-C-514-ONNCCE-2019 and ASTM G57, the values obtained less than 10 kΩ·cm are in the range of excessive porosity; this means it promotes a high susceptibility to corrosion damage, as it happened to the real-life structure. As is well known, the ER of concrete is associated with the microstructure of the pore structure, cement matrix, pore size distribution, and porosity, and all of them depend on the hydration degree of the cement paste. The factors that control these parameters are the relative humidity, concrete temperature, ion concentration, and their mobility in the cement chemistry, as well as the pore solution, cement content, and proportion of water–cement [32,33].

The description above indicates that the concrete used for the construction of the structures did not have good construction practices, from the mix design to the curing process, which should provide surface protection to concrete structures, if the curing process is carried out correctly. Therefore, regarding resistivity, the structure does not meet the required performance criteria as shown in Tables 2 and 3.

To support the results mentioned above, it is considered that concrete is a non-conductive composite material, but it has an ionically conductive cementitious matrix; thus, the hydration process will result in microstructural fluctuations, producing a capillary decrement, connectivity pore, and increment of pore size and tortuosity. Refining the pore structure in the long term, further than the post-curing period, will have an important impact on the properties of permeation and should be assessed [34]. Thus, electrical conductivity tests for concrete will be performed basically by the associated capillary porosity inside the binder, which is influenced by hydration and pozzolanic reaction. This will produce microstructural alterations in the pore network, and temporal decrements in the measured conductivity will be obtained.

Likewise, it has been reported that the addition of FA (fly ash) and GGBS (ground granulated blast furnace slag) helps to reduce the conductivity of concretes due to the continuous refinement of the pore structure during the post-curing stage [35–37]. Regardless of the fact that the total porosity of those concretes may not necessarily be lower than the total porosity of the PC (Portland cement) concretes, their nature is more intermittent and winding due to the continuous reactions into the current pore structure [35–37].

4.3. Discussion for Porosity and Capillary Absorption

Figure 9 shows the plot for water porosity, while Figures 10 and 11 and Table 6 show the corresponding plot and kinetic parameters for capillary absorption. The obtained results related to the density are very homogeneous through the pier, no matter the location of the core tested. That means that the relationship between the weight of the concrete and its volume is a key factor in determining the resistance, durability, and load capacity of buildings and infrastructure, which depend on the dosage of the aggregate, water, and cement content, among others.

Considering the porosity scenario where water is accessible, there is a slight variation between the cores of both piers (M1C and M2T); the structural elements from M1C and M2T have greater porosity, which situates them in high porosity. The results of porosity generated from structural elements of M1C and M2T, in most cases, are located in high porosity according to Table 4, which classifies the quality of concrete as poor.

One way to understand the results obtained and described above is by explaining what happens in the cement paste, as follows: the permeation of liquid, gas, or ions into the concrete core and its interaction with the pore water and concrete constituent play a fundamental role in the structure's durability with reinforced concrete. Concrete permeation properties are altered by the size, shape, type, and distribution of pores in the cement paste and aggregate. The total pore volume is a concerning factor in the case of strength and elasticity [38]. A pore size greater than 50 nm defines the concrete's permeability, and the free water existing on these pores is responsible for the permeation of external receptor agents into the concrete [39].

Figure 12 indicates the pore sizes inside and on the concrete surface, the ions' size, and the gas molecules that enter the concrete matrix through the network of interconnected pores. At this point, it becomes important to implement quality controls through tests that quantify the durability of concrete cores taken from concrete elements, without losing sight of the importance of a good mix design to an adequate curing process.

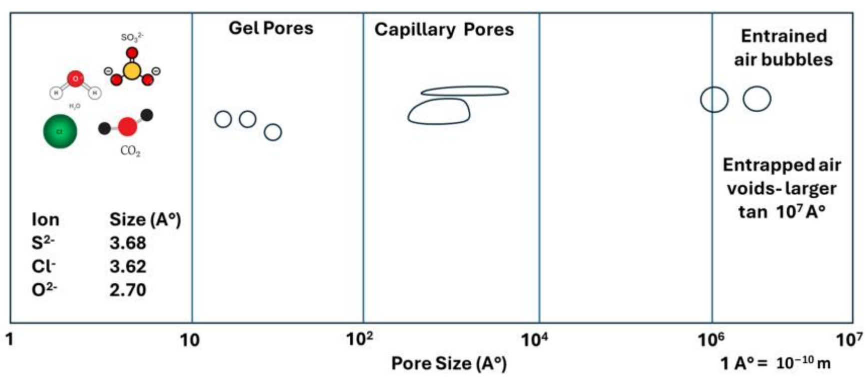

Figure 12. Ions' sizes, gas molecules, and the relative size of pores existing in the concrete (adapted from Mehta P. K. et al. (1986)) [40] and Neville et al. [15].

The sorptivity test of the water determines the water collection via capillary suction in the concrete. Therefore, sorptivity provides the measure of effectiveness and nature of curing since it is sensitive to the concrete properties close to the surface. The concretes from M1C and M2T have sorptivity values under 6 mm/h$^{1/2}$, which suggests that the concrete is of durable quality, according to Table 4. However, the results of resistivity and porosity indicate that the concrete quality is inadequate; this can be explained by the connection (permeability) between the pores and the contribution of the physical phenomenon of capillary sorption, which is carried out by the pore walls. Therefore, sorptivity values less than 3 mm/h$^{1/2}$ are related to a good curing process; for the case of M1C, the value obtained was 5 mm/h$^{1/2}$, associated with poorly cured concrete, while M2T slightly improved the curing process [41].

The permeability coefficient was amplified with the increment in the absorption of surface water. As it is known, water absorption and permeability were altered due to the pore structure of cement paste and the transmission of liquid from the surface into the interior. Thus, this indicated that the absorption of surface water offers great effects on permeability [42]. Therefore, sorption depends on the capillary pressure as well as on the effective porosity. Capillary pressure is associated with the size of the pore by the Young–Laplace equation, whereas effective porosity is related to the pore space in the capillary and gel pores. Moreover, different pore sizes produce different capillary pressures, and concrete capillary pressure is obtained using the average pore size.

The durability indicator values of the actual concrete for a particular environment will contribute to estimating the resistance of the structure fabricated with concrete against deterioration. In the case of reinforcement steel corrosion, the testing of cover concrete helps in estimating the ingress of external harmful substances in the concrete. In the performance-based approach, the test methods and acceptance criteria should be clearly specified, and it can be carried out in either the pre-qualification or construction structure quality acceptance stage [43].

A tight and highly impermeable pore structure is fundamental for the durability of concrete [44,45]. It is important to mention that concrete durability is basically associated with the transport properties and its chemical composition [46–48]. Thus, penetrability includes diverse mechanisms and is measurable according to different transport mechanisms, e.g., sorption, permeation, migration, diffusion, and convection [47,49]. Consequently, the specifications utilized in any construction activity play an essential role in the long-term durability of a structure. In addition, the concrete strength and microstructure are dependent on the water–cement proportion, although the strength depends directly on the total pore volume.

However, in the case of durability, the size, type, and continuity of the pores in the concrete are vital. This indicates that the quality of cover concrete has more importance since it depends on the construction process and the curing effectiveness, such as the variables of construction processing, e.g., compaction, placing, and curing, among others, which affect the quality of the concrete surface zone and have an effect on durability due to the movement of aggressive agents into the concrete. Hence, the main factors for concrete deterioration are the constituent materials, the concrete near-surface quality, and the environment's aggressiveness. Therefore, by measuring the durability parameters of actual concrete on site, the cover concrete quality of the structure is obtained. This is the basic principle of performance-based specification.

Considering that corrosion occurs, the deterioration agents (CO_2, O_2, chloride ions, and moisture) travel through the concrete cover and the corrosion process begins [50]. Thus, the quality of the concrete cover and its appropriate width are of great importance for the performance of the corrosion resistance and the prolonged durability of RC structures.

Likewise, an approach based on performance has diverse advantages in the design and construction of durable structures with respect to the prescriptive approach; this is because the factors that affect durability are verifiable, i.e., concrete cover penetrability and thickness. Some of the advantages are (i) service life calculation based on parameters of durability, (ii) easiness in the selection of materials for the concrete contractor/producer, and (iii) the verification of the final concrete properties increases the execution quality of construction practices [51].

In the literature, many works report the importance of non-destructive testing to determine concrete durability and the probability of corrosion damage to structures [52–54]. Non-destructive testing carried out in this work, which is conducted on piers that are 20 and 40 years old, provided an overview of the deterioration that these structures have suffered and, based on this, a determination of the quality of their concretes and possible corrosion damage. Similar results were obtained by Rama Seshu et al. [55], who reported durability tests on a T-beam girder bridge, constructed across a river in India. From their results, they were able to conclude that the concrete of this bridge is of average quality and even recommend repairs to the bridge. Another similar work was reported by Malek Jedidi et al. [56]; in this work, an experimental study was conducted on a public-use building, located in Sfax, south of Tunisia, which has structural disorders using non-destructive testing. Their results show that the concrete has an average quality and that the structure presents great corrosion progress. Comparing these works with our work, which reported poor-quality concrete, the difference in the results evaluating the quality of the concrete can be attributed to the fact that the piers are in more aggressive environmental conditions than the bridge and the building reported by Rama Seshu et al. [55] and Malek Jedidi et al. [56], respectively.

5. Conclusions

In this work, non-destructive testing was used to evaluate the concrete of piers that are 20 and 40 years old. The ultrasonic pulse velocity analysis shows that the concrete of the M2T tourist pier has less compaction; this is attributed to the fact that it was not designed to support loads like the M1C load pier. The electrical resistivity tests carried out show that both piers have a large number of interconnected pores, which favor the flow of electric current and imply a high risk of corrosion of the reinforcing steel. The M2T pier has the lowest resistivity, which is an indicator of a greater diffusivity of ions towards the interior of the concrete and is caused by the greater age of this pier, compared to the M1C pier. The porosity test indicates that both piers have concrete with inadequate durability. In this case, the concrete of the M1C pier has a higher porosity, which is attributed to physical defects in the concrete caused by the handling of loads on the pier. On the other hand, considering the age of the piers, the sorptivity results indicate that the concrete of both piers is unsuitable for aggressive environments. Together, these non-destructive tests allow for the conclusion that both piers present poor-quality concrete and the structures have a high risk of corrosion. These problems of the infrastructure are caused by the age of the concrete and the exposure to an aggressive environment.

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