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The Georadar in the Evaluation of Reinforced Concrete Structures Affected by Corrosion

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Abstract: Ground Penetrating Radar (GPR) is a geophysical method that has several applications in the field of civil engineering, with one of the largest fields being the evaluation of the technical state of the affected reinforced concrete structures by corrosion. In Cuba, this method has not been widely used as a non destructive test (NDT), largely due to the lack of knowledge of its potential in civil engineering. This article performs a critical analysis of some investigations in which the georadar is applied to evaluate the technical state of tunnels, bridges and buildings. The regulatory framework that protects the use of the georadar as NDT in the world and the applications that it has had so far in Cuba are addressed. The electromagnetic responses of the method to various injuries and causes that cause damage to reinforced concrete such as fractures, cavities, areas of humidity, chloride penetration and corrosion itself are also presented.
Key words: GPR; concrete; corrosion

1. Introduction

The durability of concrete structure depends on the type and strength of the degradation mechanism acting on the concrete structure, as well as the resistance to degradation physical factors (rheological process, corrosion, crystallization, leaching, overload, fatigue, temperature and humidity consistency). The mechanism is related to chemical phenomena (carbonization, corrosion, corrosive environmental impact, reaction between material components), and the biological mechanism is caused by the action of plants, microorganisms and animals in concrete structures [1].

As a rule, in practice, the combination of different mechanisms appears in the form of complex degradation processes, which will damage the structure and ultimately determine its service life [1]. One of the major problems affecting the service life of concrete is the corrosion of reinforcing steel. It consists of the destructive oxidation of the steel when the concrete is exposed to aggressive environments, especially when exposed to chloride ions and/or carbon dioxide. The consequences of the destructive action of oxidation are presented as a decrease in the section of the steel, cracking in the concrete and even lamination of the concrete, due to the pressures exerted by the expansive oxide and the decrease or disappearance of the adhesion between the reinforcement and the concrete [2].

Cuba, a narrow and elongated archipelago, has a tropical climate with high relative humidity. Because it is completely surrounded by the ocean and subject to the continuous action of marine aerosols, structures close to the coast are most affected by these processes. This situation led to the serious and early deterioration of reinforced concrete structures due to the corrosion of reinforcement, which damaged the technical status of buildings and facilities in the country.

For the evaluation of the technical condition of reinforced concrete structures, there are destructive and non-destructive tests or techniques. Destructive tests include: extraction and destruction of concrete samples and collection of reinforcement samples [3]. Non-destructive testing includes hardness or resilience testing, ultrasonic testing, corrosion testing, electrical resistivity, infrared thermography, radioactive and electromagnetic methods.

In view of this, the georadar or Ground Penetrating Radar (GPR) is a non-destructive method suitable for corrosion studies, since with the analysis of the amplitude of radar image and the reflected wave signal, values related to the degree or level of corrosion and its location can be obtained.

The main applications of georadar in civil engineering are in geotechnical studies, foundations and to evaluate the technical condition of pavements. Although important steps have been taken in using this technology to study reinforced concrete, its usefulness and versatility is practically unknown by the community of engineers and architects in Cuba. The purpose of this paper is to show the potential of GPR technology as a method for studying the pathology of corroded reinforced concrete structures.

2. Materials and Methods

A literature review has been carried out in this work. The potential of georadar as a non-destructive test technology to evaluate the technical condition of reinforced concrete structures affected by corrosion.

3. Results

Among all the non-destructive technologies, GPR has the greatest advantage because of its wide versatility. It can almost be used to study most diseases affecting reinforced concrete structures in the field of defect science. One of the biggest advantages is that it can quickly and accurately obtain two-dimensional or three-dimensional images of the structure according to the operation frequency. In addition, it also provides the possibility of real-time visualization of data and "minimal" processing with equipment. All these make georadar particularly useful in civil engineering.

3.1 Principles of physics

The georadar includes transmitting high-frequency wave pulses to the medium and receiving reflected and diffracted waves generated by the change of electromagnetic characteristics of the medium. The equipment basically consists of transmitting and receiving antennas, which may be in the same device or separate, and a central unit that controls the emission and reception of the signals. The transmitting antenna emits electromagnetic pulse, which is emitted through the interior of the medium and reflected by all surfaces with different electrical impedance. The reflections on different interfaces are collected by the receiving antenna, and the sum of all these reflections will form the response of the material and be recorded in the track (A-scan). Over time, a group of traces recorded in the material are called radar image (B-scan), Fig. 1.

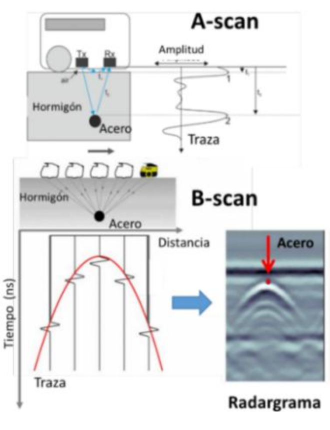

Figure 1. The ground penetrating radar in A-scan (trace) and B-scan (radargram) variants.

The ground penetrating radar in A-scan (trace) and B-scan (radargram) variants is used for data acquisition. The B-scan variant shows the characteristic reflection hyperbola of steel embedded in concrete or other objects such as pipes and cables. The apex of the hyperbola shows the position of the steel. Taken from Tosti and Ferrante [4]. Author's arrangements.

The propagation of wave in the material is determined by the electromagnetic parameters: conductivity (σ), dielectric constant (ε) and magnetic property. Therefore, the reflection of wave is caused by the comparison of these properties, which can characterize the medium.

The electromagnetic properties of a medium are closely related to other physical properties (density, moisture content, porosity), to its composition and small-scale structure. That is why it has begun to be used in the characterization of materials. Specifically, its application in the study of concrete has given very promising results. [6]

Permittivity or dielectric constant is a measure of the polarization capacity of a material in the presence of an electric field. Its range of variation is between 1 (air) and 81 (water at 20ºC). The response of the GPR is highly dependent on the dielectric constant, since most materials are non-magnetic (and dielectric (σ=0). Under these conditions, the propagation speed (Equation 1) depends only on the speed of light in the vacuum (C=3 × 108 m/s) and the relative dielectric constant of the medium [7].

$$V_{\mathrm{m}} = \frac{C}{\sqrt{E_r}} = \frac{3\times10^8}{\sqrt{E_r}} m/s = \frac{30}{\sqrt{E_r}} cm/ns$$

Equation 1

The dielectric constant of building materials is related to their volumetric properties and can be used in the identification of defects or depletions within structures. In the case of concrete, it correlates with the type of aggregate, water-cement ratio and chloride content. In general, the permittivity value is usually taken from tables or determined experimentally. In the process of electromagnetic wave propagation through the medium, energy loss (attenuation) will occur due to different reasons. This decline in wave amplitude determines the maximum theoretical depth that can be reached in each case. Other effects, such as low signal-to-noise ratio, equipment problems or improper handling, will make this value still lower than expected in practice [8]. When the wave passes through the material, the phenomenon of signal absorption and scattering will always exist.

A very common way to characterize an antenna is through its transmitted center frequency. According to Equation 2, the wavelength of the transmitted pulse depends on the frequency and the wave velocity in the medium.

$$\lambda = \frac{v}{f}$$

Equation 2

Where λ is the wavelength, v is the wave velocity and f is the frequency.

At higher transmission frequencies, the wave propagation attenuation is greater. For this reason, the antenna must be selected according to the specific application of the radar. Therefore, the low frequency (< 100 MHz) antenna has great penetration capability (> 9 m), but its resolution is low. As far as it is concerned, the depth of high-resolution antenna to the terrain is very small, which can distinguish very small objects.

When the antenna emits a pulse, it has a certain polarity, which can be positive or negative. Whether the reflected signal can retain the polarization of the original pulse depends on the difference between the dielectric values of materials [9]. The parameter R (Equation 3) represents the polarity and amplitude of the reflection, which is called the reflection coefficient.

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

Equation 3

Where, ε 1 and ε 2 are the relative permittivity of the first and second media.

The size of the reflection coefficient R is directly related to the reflection amplitude of the received wave, that is, the definition of the reflector observed in the radar image. The polarity of the received signal is also valuable information about the object causing the reflection.

The reflector in the radar image can be a reflection hyperbola or a coplanar reflection. The reflection or diffraction hyperbola occurs when the wave is reflected by "objects" immersed in the surrounding medium, such as steel embedded in concrete (Figure 1), objects and pipes. They also occur in sharp areas where the dielectric constant changes. Coplanar reflectors are observed in large objects that are in plane-parallel contact or whose wavefronts treat them as surfaces. This type of reflector can be distinguished in dry concrete-wet concrete, concrete-rock, pavement layer and other contacts.

3.2 Corrosion of reinforced concrete

Corrosion of reinforced concrete is one of the most common causes of deterioration in this material [10, 11]. When the concrete protection corresponding to each structure changes, corrosion will occur and a layer of passive concrete - steel interface will be formed. Concrete provides corrosion protection for reinforcement, because the oxygen in this material forms an oxide film on the reinforcement, forming a passivation layer to prevent deep corrosion [12]. Once exposed, reinforcement embedded in concrete is vulnerable to corrosion and is not protected by $pH > 10.5$. However, there are two chemical components that can destroy the passive layer without damaging the concrete. Carbon and chloride ions are the main causes of depassivation of the reinforcement, and therefore the main trigger factor of reinforcement corrosion [13].

The corrosion process is caused by the diffusion of oxygen, carbon dioxide or chloride ions in concrete pores. These substances, combined with environmental humidity, accelerate the deterioration of steel.

A concrete manufactured with a high ratio, poor compaction, segregation of the mix, poor curing and premature drying due to the effects of wind or solar radiation, becomes a concrete with high porosity and permeability in the coating area, which facilitates the entry of aggressive substances that corrode the reinforcement and deteriorate the structural element.

3.3 GPR application

The most famous documents in the world are analyzed, which involve the use of ground penetrating radar technology to evaluate the technical status of different reinforced concrete structures affected by corrosion.

3.4 GPR in the study of buildings, tunnels and bridges

Perez Gracia et al. [14] developed a method to study the reinforced concrete foundation of a building in Valencia, Spain, and determine the water content of the floor. Measurements were taken at two different times, in dry weather and in rainy weather with four types of antennas. Using a 1.5 GHz antenna, steel can be easily detected from the reflection hyperbola. Cracked areas are detected by sharp changes in amplitude. According to the author, the possible wet area is related to the low reflection and low wave velocity. Hugenschmidt and Kalogeropoulos [15] also carried out similar research, using different frequencies (1.5 GHz, 900 MHz and 400 MHz). Through these three antennas, embedded steel can be detected, but the 1.5 GHz antenna, as in Perez-Gracia et al. [14], is the ideal antenna for this study.

Dinh et al. [16] conducted a study in the underground parking lot to understand whether the embedded steel is corroded. It is also detected that the signal attenuates to the area at the bottom of the concrete slab (Figure 2). The decrease of amplitude is related to the high humidity in this area, which leads to a sharp decline in the propagation speed of waves. This area can be designated as a corrosion area.

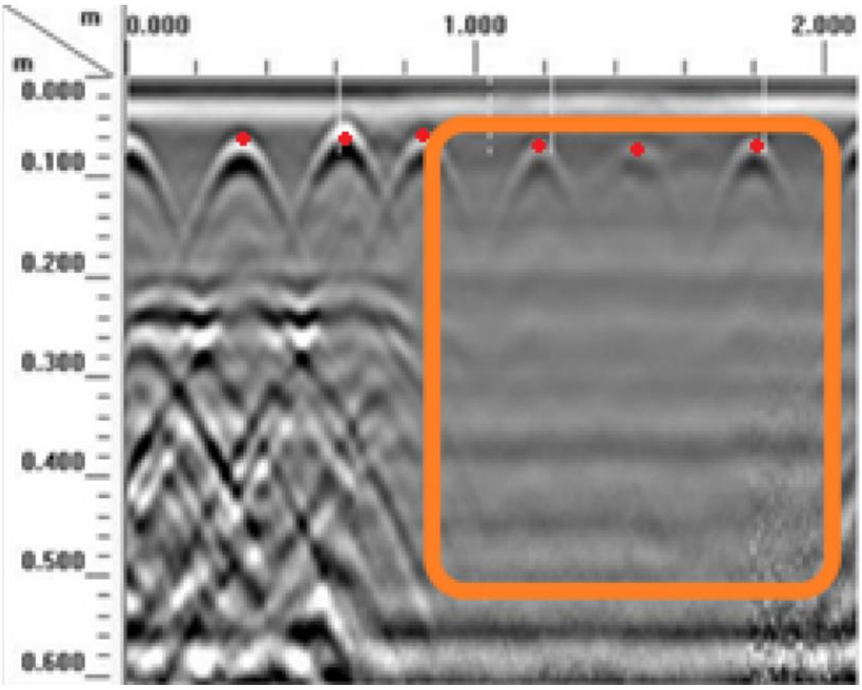

Figure 2. The location of the steel with red dots and the maximum humidity area and corrosion area of the steel in the orange box. Source: Dinh et al. [16].

In order to delimit the corroded area of reinforcement and determine other damages, such as cracks, dampness and caking, Solla et al., [17] used two NDT: ground-penetrating radar and infrared thermography with 2.3 GHz antenna. According to the author, the propagation speed decreases with the increase of water content in the material. After that, the oxide particles occupy the pores in the concrete, and the volume increases, resulting in an increase in the amplitude of the reflected signal. During the migration phase of chlorides and oxides, the frequency spectrum decreases and as the diameter of the steel decreases, the amplitude of the signal decreases. This made it possible to characterize each of the pathologies from a joint analysis, taking into account the variation of the wave amplitude, the wave propagation speed, the amplitude of the spectrum and the polarity of the signal. Through the infrared thermography, according to the change of thermal characteristics, it can be determined whether the attenuated signal in the radar image is caused by the high water content or the mineral salt content caused by the building close to the sea, because the temperature caused by humidity is lower than the temperature of mineral salt.

The main application of ground penetrating radar in tunnel diagnosis is to determine the thickness and condition of the wall, including the analysis of the state of reinforcement, and the study of the possible entities between concrete and rock [6]. Parkinson and Ékes [18] performed a survey with a 1 GHz antenna to identify construction problems in a tunnel.

Reinforcing steels were detected as well as voids between the reinforced concrete and the rock; the latter were identified on the radargram as having greater amplitude in the separation line between the concrete and the bedrock, as if it were a "bright spot". Areas were defined with low quality concrete, which was porous and air-filled. In addition, pieces of wood that were impregnated in the concrete solution were identified, which are characterized in the radargram by wide parallel bands of great amplitude. This has been confirmed by some boreholes.

Cassidy et al. [19] developed a study to detect objects under subway tunnels. Coherent, strong and uniform hyperbolas were ob-served that were regularly spaced as a result of the buried reinforcement steels. In general, the fracture area is distinguished by the strong contraction of amplitude in the ground penetrating radar image [19, 20, 21], and the reflection weakness area is due to the water leakage in the fracture area [21].

Prego et al. [22] used 1 GHz antenna to investigate the construction phase of a high-speed railway tunnel in Galicia, Spain. Through the radar image, the thickness of gunite can be checked. Due to the existence of steel fibers gathered during the filling process, the thickness of gunite is heterogeneous and the reflection amplitude increases. In addition, taking into account the change in the amplitude of the searchlight, they drew a map of wet areas and water bodies.

GPR is also used as a diagnostic tool for bridges built of natural glass or concrete to determine the position of reinforcement on the concrete slab, study the condition of concrete coating, and estimate the size of the concrete slab and its possible degradation. Kim et al. [23] conducted several measurements with ground penetrating radar on a bridge in Missouri, which has a 1.5 GHz antenna. These measurements were carried out at different times of the year. It is emphasized that they do not change much. However, according to the size of the reflection intensity, they are slightly higher in the wet period than in the dry period, and the arrival time of the wave in the wet condition is longer than in the dry condition. The location of reinforcement was determined, and two areas with low amplitude and increased wave propagation time related to high water content and chloride concentration were delineated, which aggravated the corrosion of steel. On the other hand, Ekes, [24] determined the position and spacing of the steel on the main beam of the bridge.

Morris et al. [25] determined that the concrete coverage is insufficient, which leads to a high possibility of steel bar exposure. In addition, due to the comparison of the dielectric constants of concrete and air and the high reflectivity, they linked the maximum amplitude area with the existence of the most consolidated concrete and found an object. Kim et al., [23], Ekes, [24], Morris et al., [25] Istiaque et al., [26] and Beben et al. [27] use antennas above 1 GHz to study bridges.

3.5 Humidity study

Laurens et al. [28] used 1.5 GHz antenna to test the influence of humidity on electromagnetic wave propagation through ground penetrating radar. Therefore, there is a direct relationship between water saturation and dielectric constant in concrete, that is, with the increase of water saturation, the dielectric constant increases. The authors also defined the effect of humidity on amplitude and showed that there is an inverse relationship with amplitude.

Some studies estimate the free water content in concrete by studying different electromagnetic wave parameters [28]. Other key points are to characterize the porous system of hardened concrete, or determine the volume water content in concrete, and estimate the water permeability. Some people even analyzed the relationship between the wave parameters recorded by GPR and some indicators related to durability, especially the water and chloride content in concrete [6].

3.6 Determination of steel radius

Measuring the radius of steel with ground penetrating radar is an extremely complex process, which is mainly carried out in experimental work. In this sense, several mathematical formulas have been developed to estimate the radius of steel to a certain extent according to the reflection hyperbola. These include the equations of Shihab et al. [29] and Lakshmi et al. [30]. In recent years, automatic algorithms have been developed to detect and interpret GPR data based on typical hyperbolic symbols.

3.7 Experimental study on determining the degree of corrosion

A common method for corrosion test of reinforced concrete is to immerse the reinforced concrete slab in 5% sodium chloride solution [31-34] to accelerate the corrosion process. After a certain time, the sample is extracted and an electric current is applied in the range of 1 Amperes and 10 Volts, then it is measured with the GPR, either punctually or by means of profiles. This test simulates an electrochemical cell, in which one steel is used as the cathode and the other steel is used as the anode, so as to conduct the reduction and oxidation process with reinforced concrete as the medium (Fig. 3). Through this method, the change of electromagnetic signal in each corrosion stage can be observed through continuous measurement, so as to establish a comparative standard for evaluating the corrosion degree of different reinforced concrete structures.

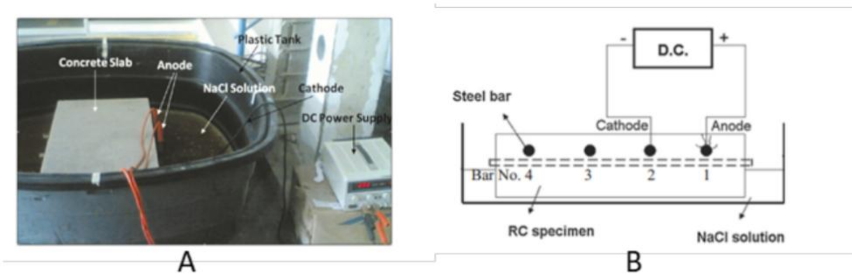

Figure 3. (A) Typical test and (B) The concept outline of anode-cathode.

(A) Typical test for corrosion of reinforced concrete. Source: Zaki et al. [34]. (B) The concept outline of anode-cathode clearly shows that in reinforced concrete samples, a kind of steel acts as cathode (reduction) and anode (oxidation) through current when immersed in NaCl solution. Source: Hong et al. [32].

In order to determine the damage caused by concrete slab corrosion, Kabir and Zaki [35] adopted the methods of GPR and half-cell potential method (HCP). In this case, the steel is placed in sodium chloride solution and impacted with direct current for 1, 3 and 7 days. The steel is then embedded in the concrete mixture. After 28 days of curing, the measurement was carried out with an antenna of 2 GHz frequency in three ways: A-scan, B-scan and C-scan (Fig. 4 A, B and C). It was observed that the first type of steel without current supply remained in perfect condition at high strength; on the other hand, with the increase of corrosion exposure days, the vibration amplitude increased, which was proved in the red bar representing the most severely corroded steel.

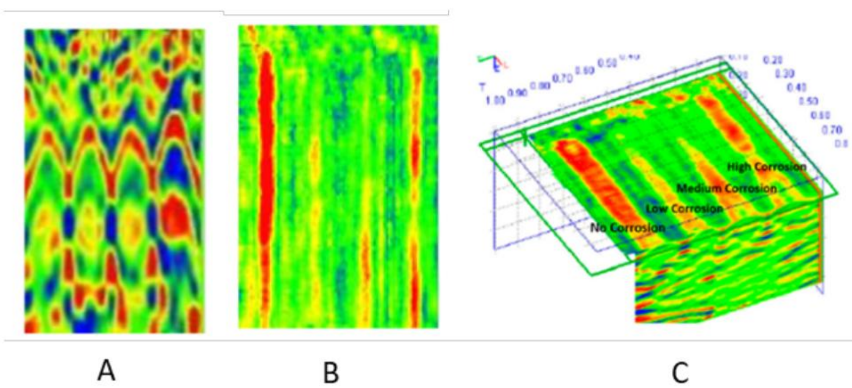

Figure 4. Measurement results.

Measurement results: (A) B-scan, (B) C-scan and (C) 3D image. From left to right: non-corrosive steel, low corrosive steel, medium corrosive steel and high corrosive steel. Kabir and Zaki [35].

Lai et al. [36] set guidelines for GPR corrosion research, and Kabir and Zaki [35] compared the results obtained with those of HCP. On the basis of detecting the corrosion of reinforcement, the author timely measured three different stages: sodium chloride pollution stage, dewaxing stage and corrosion stage. They considered three aspects to explain the changes: the propagation time of the wave, the amplitude of the received signal and the peak of the spectrum frequency. It is detected that the maximum positive amplitude of reflected wave changes in different corrosion stages. In the NaCl pollution stage, the amplitude is very high. In the second stage, due to the dewaxing of reinforcement and the reduction of concrete pH value, the concrete pH value decreased, but with the increase of corrosion, the amplitude began to increase with the passage of time. The propagation time of the wave is increasing at each stage, while the frequency of the spectral peak is always increasing. On the other hand, by analyzing the results of half-cell potential, it can be seen that the area with the most serious corrosion is located in the area with the highest potential.

Hong et al. [32] continued the investigations performed by Lai et al. [31], [36] and performed measurements on profiles, rather than pointwise on a reinforced concrete slab, and relied on the half-cell potential method. The authors divided the measurements into two experiments, the first with the direct action of moisture and chloride contamination and the other without the influence of chlorides. The analyses were performed in the time and frequency domain, and both the reflected and direct waves were taken. As a result, it was obtained that, for the first case, the peak frequency of the reflected signal decreases and the travel time of the wave increases. In the second case, the travel time decreases and the signal amplitude increases. Hong et al. [32] draw chloride permeability by changing the peak frequency of direct wave, which decreases with the increase of chloride content and humidity. In the latter case, the results were compared with cores extracted from the samples and analyzed by laser induced breakdown spectroscopy (LIBS), which confirmed the penetration of chloride in the sectors determined by ground penetrating radar.

A statistical relationship is established between the dielectric constant and different parameters, synthetic amplitude, corrosion degree, percentage of steel mass loss and wave propagation time [33, 37]. With the increase of corrosion degree, the dielectric constant increases, the steel mass loss rate and the wave propagation time also increase, but the amplitude decreases [37]. The depth at which the steel is located has also been taken into account; the deeper it is, the longer the travel time; and the larger the diameter and the shallower the depth at which it is located, the greater the amplitude obtained. However, Krishnarajapete, [33] proposed that under these conditions, with the increase of corrosion degree, the amplitude will be greater. This is because with the further corrosion of steel, the concrete is affected by iron oxide and small cracks appear, affecting the porosity and density of the medium [38]. With the increase of heterogeneity, GPR signals are transmitted.

Lai et al. [39] described different applications of GPR for civil engineering research in their work. The author suggests that corrosion can be divided into two stages: the initial stage of corrosion and the expansion stage of active corrosion. Initiation refers to the invasion of carbon dioxide, followed by the pollution of water and chloride to cause corrosion, which is an electrochemical process. The corrosion expansion stage is based on the dewaxing and development of the transition zone between concrete and steel, and the subsequent loss of size and thickness. These two stages have been studied by different authors using ground penetrating radar technology, and the standards obtained are not uniform. In these studies, there is a paradox when analyzing the intensity threshold process in the area where the two phases coexist.

3.8 Application of GPR in Cuba civil engineering

In Cuba, there are few reports on the use of GPR in civil engineering. This technology has been used in the diagnosis and research of buildings with great architectural value, the positioning and gypsum molding of structural elements in walls, the positioning and corrosion of steel trusses, and the positioning of hydraulic and communication service networks [40]. Recently, the National Application Engineering Corporation (ENIA) purchased a GPR from the manufacturer MALÄ with several antennas: 80 MHz, 160 MHz, 450 MHz, 750 MHz and 1.6 GHz. With the procurement of this modern equipment, the company has carried out research on the determination and geotechnical engineering evaluation of historical building foundations nationwide. Before that, they had a ground penetrating radar of the same brand as various research, which carried out different technical tasks related to civil engineering.

3.9 Legal framework

Some international organizations use GPR technology to promote some guidelines, standards or recommendations. ASCE (CI/ASCE 38-02) [41], ASTM International (ASTM C876-91) [42], (ASTM D6432-99 (2005) [43], ASTM D6432-11 (2011) [44] and ASTM D6087-08e1 (2015) [45], governed by the EuroGPR in Europe [46]. At present, Cuba has no rules to regulate the procedures required to evaluate the technical status of reinforced concrete structures through GPR.

Current Cuban standard NC-1109:2015 [47] and regulations RC-9002:2000 [48] collected hardening and ultrasonic methods to determine the compressive strength of reinforced concrete structures as non-destructive testing methods. For corrosion evaluation, the NC-695:2009 [49] standard only considers the corrosion of reinforcement to the previously prepared specimen by the electrochemical constant current method, and does not directly measure the structure. In the field of defecation and pathological analysis, the advantages of GPR as a non-destructive test for studying the pathology of reinforced concrete have not been recognized.

4. Discussion Results

Through literature research, the main characteristics of electromagnetic response of ground penetrating radar to reinforced concrete under different factors and damages are summarized. In this sense, humidity is characterized by the decrease of wave propagation speed, low temperature (through infrared thermography) [17], high dielectric constant value, signal dispersion and attenuation. Conversely, chloride penetration is determined by serious attenuation, small signal amplitude value, peak frequency of direct wave [32] and the decrease of propagation speed. The temperature of the infrared thermography [17] shows a higher value. The difference between voids or objects in concrete is the change of signal polarity, the high reflectivity of radar and the amplitude value less than that of reinforcement [17, 25]. In itself, the reinforcement is determined to have ring effect (before applying deconvolution), high amplitude value, and potential value per HCP is greater than - 200 mV [31, 35]. On the contrary, compared with uncorroded steel, the signal attenuation of corroded steel is greater, the dielectric constant value is higher, the wave propagation time is longer, and the HCP value is lower than - 350 mV [31, 35]. The amplitude behavior is generally accepted as decreasing at the beginning of corrosion and increasing at the active corrosion stage.

The antenna with higher frequency (1.5-2.6 GHz) provides better resolution, which can detect steel, determine small objects and evaluate the corrosion degree of reinforced concrete structures [17, 23, 30, 31, 34, 35, 36, 38]. The antenna with lower frequency (400-900 MHz) provides lower resolution, which is helpful to detect steel according to the thickness and spacing of steel, study pavement, tunnel and determine the thickness of concrete [19, 20-22]. Its main advantage is the depth of research, which is usually installed on larger wheels, thus speeding up data acquisition. Both antennas can detect objects, crack areas and humidity. The choice of antenna type will depend on the structure to be studied, the type of information to be obtained and the depth of research. In terms of acquisition system, A-scan is the least used, which is mainly used for high-frequency antenna in laboratory test or just-in-time test [17, 31, 34, 38]. The purpose of its use is to determine the variation in time of the amplitude and frequency peaks of the direct and reflected wave, which are indicators of changes in the electromagnetic properties of the medium. B-scan is the most common acquisition form because of its speed and versatility [16, 18-27]. It can be applied to any type of structure, and allows A-scan by taking the track of radar image, or simulate C-scan by parallel contour. In order to improve the quality of the results, this collection scheme must be perpendicular to the possible position of the steel in the concrete. As for C-scan, it is very suitable for understanding the distribution of steel. It is usually used in small areas where all possible information is desired. It takes longer to collect data using C-scan, but the quality of information is improved [19, 35].

In the references of using georadar technology to evaluate the technical condition of reinforced concrete structures, experts focused on identifying cracks and holes [17, 25], determining the concrete thickness [23, 26], and detecting steel [27, 50] and wet areas [26]. Corrosion identification is carried out according to the matching of wet areas and steel positions. These departments are defined as the departments most likely to suffer from corrosion [16, 23]. Another method is to analyze each steel and observe the change of signal amplitude when measured on the steel [31, 33, 34]. The change of amplitude in steel provides information about the change of electromagnetic properties of steel, mainly due to corrosion. Another method to directly measure structural corrosion is to rely on other methods, such as HCP. The amplitude of the GPR signal is calibrated according to the corrosion level on the steel given by HCP, and then the GPR measurement is performed on other parts of the structure [31, 35].

The experimental test of concrete samples reveals two trends of researchers. One is to explain corrosion with the increase of amplitude [4, 31, 32, 35, 36, 39, 51, 52], and the other is to explain corrosion with the decrease of amplitude [34, 37, 38]. Even if the threshold is not defined and there is no consensus, the standard that low intensity corresponds to the initial stage of corrosion and high intensity corresponds to the active stage of corrosion can be accepted.

5. Conclusion

Among the non-destructive technologies in the field of defect science, GPR has the greatest advantage in evaluating the technical status of reinforced concrete structures affected by corrosion, because it can comprehensively characterize the current diseases with high accuracy and speed.

The main applications of GPR to evaluate the technical condition of reinforced concrete structures are: the location of reinforcing steels, their spacing and to a lesser extent, their radius; identifying areas with dampness or water saturation; and the location of fracture zones, faults and voids.

In the study of reinforcement corrosion, when the amplitude of reflected wave decreases, it corresponds to the corrosion zone in the initial stage, and if the amplitude is large, it is considered as the corrosion zone in the active stage. At the same time, the polarity changes of high amplitude waves correspond to the sound and low signal intensity values, which are the characteristics of wetlands.

The technical status of using ground penetrating radar technology to study reinforced concrete structures in Cuba is still in its infancy. The development of this method requires construction companies to purchase equipment and formulate regulations for the correct application of this method.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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