Revista Facultad de Ingeniería, 31 (59), 2022, e13110

Revista Facultad de Ingeniería
Journal Homepage: https://revistas.uptc.edu.co/index.php/ingenieria

Significant Reductions in the Area in Corroded Steel and its Repercussion in Prefabricated Large-Panel Buildings

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Received: July 02, 2021 **Accepted:** December 28, 2021 **Published:** January 14, 2022

Citation:
Y.-C. Socarrás-Cordoví, L. González-Díaz, E.-R. Álvarez-Deulofeu, "Significant Reductions in the Area in Corroded Steel and its Repercussion in Prefabricated Large-Panel Buildings," *Revista Facultad de Ingeniería*, vol. 31 (59), e13110, 2022. https://doi.org/10.19053/01211129.v31.n59.2022.13110

Abstract

In Santiago of Cuba, there is an architectural heritage built with the prefabricated I-464 system, popularly known as the Great Soviet Panel, with more than 50 years of use. The buildings present damages such as the corrosion of the steel in the slabs, panels and horizontal joints between them. To analyze the earthquake-resistant

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behavior of deteriorated buildings, it is necessary to specify the peculiarities of the steel used as reinforcement of the structural elements. Destructive testing of steel is implemented, as well as correlation of non-destructive test results with concrete, in particular ultrasonic pulse velocity, moisture, and corrosion potential. Visual inspections are also performed to identify cracking patterns, carbonation advance, and surface color. Among the main results obtained is that the quality of the steel for the 3 mm diameter bars, which make up the electro welded meshes of the panels, do not comply with the current requirements for earthquake resistant design. These bars, in addition to a yield strength higher than recommended, are smooth bars with a non-ductile behavior, since they do not have a defined elastic limit. A considerable reduction in the diameters of the corroded bars in relation to the high levels of corrosion was obtained due to the high percentages of humidity undoubtedly causing an appreciable reduction of the yield strength of these bars. It is observed that, in the elements with the highest percentages of humidity, the most negative potential values and those with the highest corrosion velocity are reached.

Keywords: attack penetration; corrosion velocity; diameter reduction; large panels; precast concrete; yield stress.

Reducciones significativas de área en aceros corroídos y su repercusión en edificaciones prefabricadas de grandes paneles

Resumen

En Santiago de Cuba, existe un patrimonio edificado con el sistema prefabricado I-464, conocido popularmente como Gran Panel Soviético, con más de 50 años de explotación. Los edificios evidencian daños como la corrosión del acero en las losas, paneles y juntas horizontales entre ellos. Con la intención de analizar el comportamiento sismorresistente de las edificaciones deterioradas, se requiere precisar las peculiaridades concernientes al acero que conforma los elementos estructurales. Se recurre a la realización de ensayos destructivos al acero, así como a la correlación de los resultados de los ensayos no destructivos, en particular la velocidad del pulso ultrasónico, la humedad y el potencial de corrosión. También se realizan inspecciones visuales para precisar los patrones de fisuración, el avance de la carbonatación y el color de las superficies. Entre los principales resultados obtenidos está que la calidad del acero para las barras de diámetro 3 mm que conforman las mallas electrosoldadas de los paneles no cumple con los requerimientos actuales del diseño sismorresistente. Estas barras, además de un esfuerzo de fluencia superior al recomendado, son barras lisas con un comportamiento no dúctil, al no poseer un escalón de fluencia definido. Se obtuvo una considerable reducción de los diámetros de las barras corroídas en relación con los altos niveles de corrosión que existen a causa de los elevados porcentajes de humedad que inciden indudablemente en una reducción apreciable del esfuerzo de fluencia de esas barras. Se observa que, en los elementos con mayores porcentajes de humedad, se alcanzan los valores de potencial más negativos y los mayores valores de velocidad de corrosión.

Palabras clave: esfuerzo de fluencia; grandes paneles; hormigón prefabricado; penetración de ataque; reducción de diámetros; velocidad de corrosión.

Reduções significativas de área em aço corroído e seu impacto em edifícios pré-fabricados com grandes painéis

Resumo

Em Santiago de Cuba, existe um patrimônio construído com o sistema pré-fabricado I-464, popularmente conhecido como Grande Painel Soviético, com mais de 50 anos de funcionamento. As edificações apresentam danos como corrosão do aço nas lajes, painéis e juntas horizontais entre eles. Com o intuito de analisar o comportamento sísmico de edifícios deteriorados, é necessário especificar as particularidades relativas ao aço que compõe os elementos estruturais. Ensaios destrutivos de aço são usados, bem como a correlação de resultados de ensaios não destrutivos, em particular velocidade de pulso ultrassônico, umidade e potencial de corrosão. Inspeções visuais também são realizadas para determinar os padrões de rachaduras, o progresso da carbonatação e a cor das superfícies. Entre os principais resultados obtidos está que a qualidade do aço para as barras de 3 mm de diâmetro que compõem a malha eletrossoldada dos painéis não atende aos requisitos atuais de projeto resistente a terremotos. Essas barras, além de uma tensão de escoamento superior à recomendada, são barras lisas com comportamento não dúctil, pois não possuem limite de escoamento definido. Obteve-se uma redução considerável nos diâmetros das barras corroídas em relação aos altos níveis de corrosão existentes devido às altas porcentagens de umidade que indubitavelmente afetam uma redução apreciável da tensão de escoamento dessas barras. Observa-se que, nos elementos com maiores porcentagens de umidade, são atingidos os valores de potencial mais negativos e os maiores valores de taxa de corrosão.

Palavras-chave: concreto pré-fabricado; estresse rastejante; grandes painéis; penetração de ataque; redução do diâmetro; taxa de corrosão.

I. INTRODUCTION

In a 26 year period alone, 665 buildings were erected in the municipality of Santiago of Cuba, built with the prefabricated I-464 system, popularly known as the Great Soviet Panel (GSP). For a total of 769 buildings in the province of the same name. Buildings were built according to two types (with balcony and without balcony) and fundamentally 4 or 5 levels.

In the conception of this prefabricated system, adequate criteria were used to be implemented in areas of high seismic danger. Despite the design codes of the time when the prefabricated system emerged, these buildings have shown adequate behavior in the face of large earthquakes, both in Chile in 1985, 2010 and 2012 and in Armenia in 1988 [1-2]. The load transmission system is crossed and the horizontal and vertical joints, wet, rigid at the level of the superstructure. However, the behavior of buildings in Santiago of Cuba is worrying, since they have been in operation for more than 50 years and present factors that condition the appearance of potential seismic damage, such as pathological damage and structural modifications

In [3] they show that the representative pathological damage (80%) is humidity, which is manifested through the corrosion of steel (60%) mainly in the slabs, panels, and horizontal joints between them. This phenomenon of corrosion is one of the main causes of durability of concrete according to [4]. It can generate from cracks, detachment or bending of the concrete, delamination of the steel due to loss of adhesion of concrete to the steel bars, among others, with the consequent loss of strength and rigidity of the structure. Hence, its impact must be taken into account when analyzing the earthquake-resistant behavior of buildings built with the prefabricated system (GSP).

To fulfill this purpose, it is necessary to specify the peculiarities of the reinforcing steel of the structural elements. In particular, the diameters of the steels, the coating, the spacing and the yield point, both in elements with the presence of pathological damage, and in those that present good technical-constructive state. For this, destructive tests are carried out on the steel, as well as the results of the non-destructive tests carried out by [5-6]; specifically, ultrasonic speed, humidity, and corrosion potential. Visual inspections are also performed to identify cracking patterns, carbonation advance, and surface color.

Among the main results obtained is that the reinforcement meshes in the precast elements of the GSP system were formed both with steels of good ductility (diameters 9.5 and 12 mm) and with hard steels (diameters of 3, 6 and 8 mm). In particular, the quality of the steel for the 3 mm diameter bars, which make up the electrowelded meshes of the panels, does not meet current earthquake-resistant design requirements. These bars, in addition to a yield point higher than recommended, are smooth bars with a non-ductile behavior, since they do not have a defined yield level.

In the elements with pathological damage, a considerable reduction in the diameters of the corroded bars was obtained, in relation to the high levels of corrosion due to the high percentages of humidity. This reduction in the diameters of the corroded bars results in an appreciable reduction (37.5%) in their yield strength.

To confirm whether the reductions in the diameter of the steel bars are within the admissible ranges according to the quality of the concrete and the defined corrosion level, the values of the corrosion velocity were calculated for each type of steel bar. The calculated values are in accordance with the high level of corrosion, which is evidenced in the elements with pathological damage of the inspected buildings. Observing that, in the elements with higher percentages of humidity, the most negative potential values and the highest values of corrosion velocity are reached.

To fulfill this purpose, it is necessary to specify the peculiarities of the reinforcing structural steel. In particular, the diameters of the steel bars, the covering, the spacing, as well as its yield strength, both in elements with the presence of pathological damage and those that show good technical-constructive state.

For this, destructive tests are carried out on steel, as well as the results of non-destructive tests carried out by [5-6]; specifically, the velocity of the ultrasonic pulse, the humidity, and the corrosion potential. Visual inspections are also performed to pinpoint cracking patterns, carbonation progress, and surface color. Among the main results obtained there are the considerable reduction in the diameters of the corroded bars in relation to the high levels of corrosion due to the high percentages of humidity. This also affects an appreciable reduction in the yield stress of these bars.

II. MATERIALS AND METHODS

The investigation was structured in three stages as explained below.

Stage I: A slab and a panel were chosen, stored in the precast plant "Gran Panel Santiago", which were previously studied by [6], to obtain the compressive strength of precast concrete (f'c) through destructive tests to concrete. Then, these elements were demolished, the diameters of the bars and the thickness of the coating were measured with a caliper, and the spacings between bars were specified with a tape measure.

An experimental program of destructive tests was also carried out on control samples of each type of steel, to define the yield stress (fy) six 8 mm diameter specimens, five of 6 mm, six of 3 mm, six of 12 mm, and three of 9.5 mm were tested, all with a length of 15 cm. The MTE 300 universal machine and a clamp were used in the tensile test, as specified in the standard [7]. The specimens were subjected to a load that increased gradually until reaching the breaking point, defining various phases such as elastic deformation, creep, and plastic deformation.

Stage II: Visual inspections of buildings in operation were carried out and the results of non-destructive tests of [5-6] were evaluated. Specifically, in 8 prefabricated elements with pathological damage, the cracking patterns, the advance of carbonation and the color of the surfaces are specified, which allowed defining the level of corrosion; to estimate it, the corrosion damage indicators defined by [8] were used. The diameter of the corroded bars was determined in the areas where the unprotected steel with signs of corrosion was found, after removing all the rust, at least ten diameter measurements were taken per type of steel on each element. In 11 elements in good technical constructive condition, which are part of buildings in operation, the diameter of the steel bars, the spacing between them, and the thickness of the coating were verified with the reinforcement detector.

Stage III: The yield stress of the corroded bars was estimated using equation (1) [9].

$$fy' = (1 - 0.005\,Qcorr)fy \quad (1)$$

Where Qcorr is the percentage of mass loss of steel due to corrosion and is calculated by the equation (2).

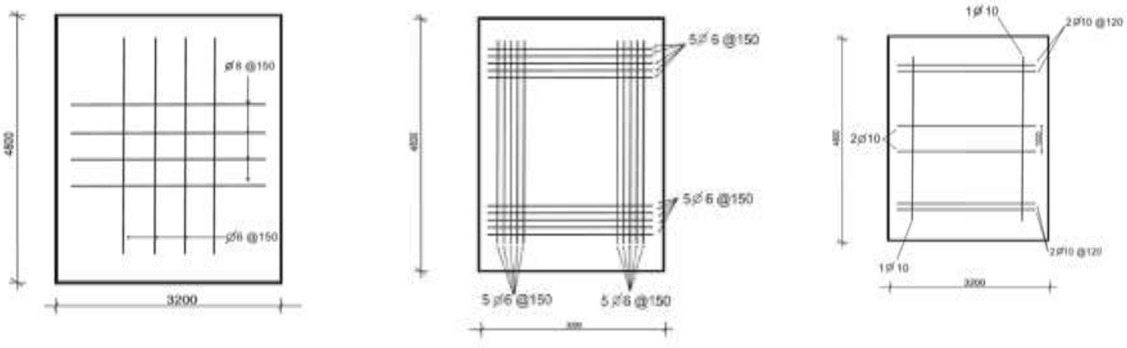
$$Qcorr = [1- (\O r / \O o)\ 2]\ 100\% \quad (2)$$

fy´, fy are the yield stresses of the corroded and uncorroded bars, respectively.

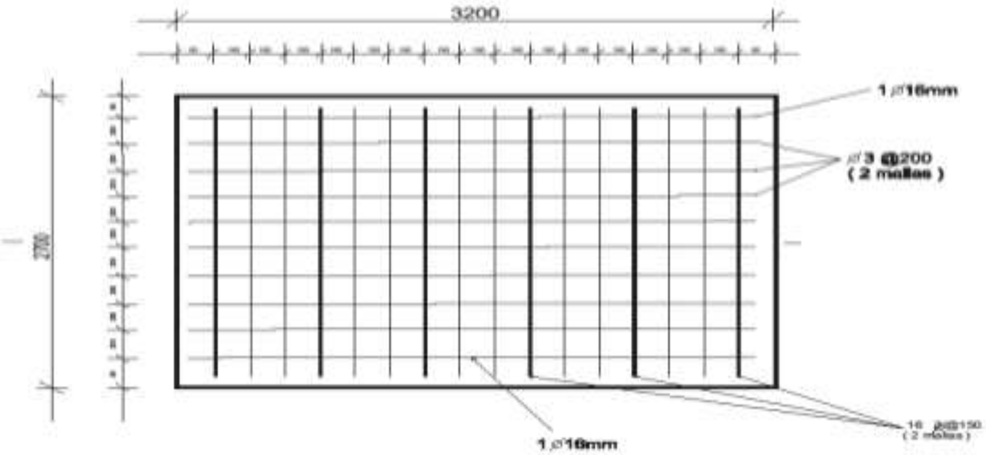
Ør, Øo are the diameters of the corroded and uncorroded bars, respectively.

III. RESULTS

The demolition of the prefabricated elements allowed us to know that the slab was made up of a double electro-welded mesh of 6 and 8 mm smooth steels, with a shear reinforcement on the edges at the bottom made of 9.5 mm corrugated steel. The panel had a double welded steel mesh of 3 mm, a perimeter reinforcement of corrugated steel of 12 mm, and two bars of 12 mm in the longitudinal direction of the panel every 600 mm. The coatings were 30 mm on both elements. In the 11 elements in good condition, these results were verified (See figure 1). Table 1 shows the values of fy.



A) Reinforcement of slabs



B) Reinforcement of panels

Fig. 1. Reinforcement of slabs and panels.

In the 8 elements with pathological damage inspected, generalized cracks were observed, with detachment of the coating and the advance of the carbonation front, which exceeds the coating (See figure 2), allowing to define the Corrosion Level IV, according to the indicators of [8]. Taking into account the average values of the corroded diameters by type of steel, in these elements with pathological damage, the reduction in diameter obtained is approximately 50% in all cases and Qcorr is assumed equal to 75%, obtaining the values of fy' which are also shown in table 1.

Fig. 2. Elements showing the corrosion of steel.

Table 1. Yield stress of the steels of the precast elements.

Steel	Øo (mm)	fy (MPa)	fy´ (MPa)
Corrugated	9.5	328.72	-
	12	324.43	202.76
Smooth	3	948.58	592.86
	6	397.40	248.37
	8	554.62	346.63

DOI: https://doi.org/10.19053/01211129.v31.n59.2022.13110

IV. DISCUSSION

The values of fy obtained for the 9.5 mm and 12 mm steel diameters are slightly higher than 300 MPa. According to [10] these steels are classified as ordinary grade A-30, now G-40 according to the standard [11] and are characterized by being steels with good ductility. When evaluating the force-displacement curves of the 3 mm, 6 mm, and 8 mm diameter bars, it can be seen that they are hard steels, because the creep step is imperceptible. The values of fy are between 397.40 - 948.58 MPa. These results are adjusted to the type of steel used in the periods of emergence of the precast system and its implementation in Cuba. In the report [12] it is collected that in the period 1911-1959 steels with fy from 232-351MPa were used, and between 1959-1966 from 232-703 MPa. According to said report, steels with fy above 351 MPa classify as hard steels.

When referring to the hard steels used in Cuba, [10] specifies that their mechanical properties place them at an intermediate point between rolled and hot drawn steels, and steels with a high elastic limit. He points out that the values of fy are between 450-850 MPa, for diameters between 3 and 10 mm and that they were generally supplied in the form of rolls. The previous results were corroborated when documents and plans were consulted in the files of Project Company No. 15, in charge of designing the buildings. R. Balart and L. Rodríguez (personal communication, December 2018), two founding civil engineers of the “Gran Panel Soviético” Precast Plant in Santiago de Cuba, also agree with these results.

When the properties of the steels are verified with the current requirements of the earthquake-resistant design contemplated by the code [13], it is concluded that the quality of the steel is not met for 3 mm diameters. Corrugated bars and wires are required, as well as ductile steels, a requirement fulfilled only by the 9.5 and 12 mm bars. Adequate ductility, according to [14] is necessary for the steel to be able to dissipate the energy induced by a severe earthquake.

On the damaged elements evaluated, it can be stated that in four of them there is a 90% probability that corrosion is occurring, which is likely for potential values lower than - 350 mV as established by the standard [15]. The results of the velocity of the ultrasonic pulse allow to conclude that the concrete is low quality, estimating [16] and evaluating the potential intervals, the concrete is wet carbonated according to [17] because of the high percentages of humidity, as specified by [5]. In all the elements with good technical constructive condition, the concrete is of medium quality, according to the values of the sclerometric index and the velocity of the ultrasound, as prescribed by the original project (See Table 2).

Table 2. Corrosion potential, ultrasonic velocity, sclerometer, percent moisture [5-6].

Elements with pathological damage				**Elements without pathological damage**	
	Corrosion potential (mV)	**ultrasonic velocity (m/s)**	**moisture percentage (%)**	**sclerometer**	**ultrasonic velocity (m/s)**
1	-324	921	50.5	34	3000
2	-362	539	45	34	3000
3	-325	2000	52.4	43	3200
4	-379	309	53.4	34	3000
5	-301	2117	47.9	34	3000
6	-167	3233	33.2	37	3000
7	-385	320	57.8	34	3000
8	-390	400	58	30	3000
9				39	2800
10				39	2900
11				39	2900

In [18] it is suggested that the method of measuring the diameter of corroded bars be used only when the decrease in section is noticeable, which normally occurs in cases of corrosion by chlorides. For this reason, it was only used in the inspected elements that showed a high degree of corrosion; however, it was not possible to measure the diameter of the corroded bars in all the elements or with the accuracy required, some of the bars measured could not be fully separated from the concrete, limiting the measurement in various radial directions. The measurement of the diameter of the bars is precise with the extraction of steel core samples, and this was not feasible because all the buildings are inhabited.

To confirm whether the reductions in the diameter of the steel bars are within the admissible ranges according to the quality of the concrete and the level of corrosion defined, the values of the corrosion velocity (Icorr) were calculated for each type of steel bar. For this, the time in which the aggressive reached the armor (ti) is deduced, which is determined according to equation (3).

$$ti = \left(\frac{X}{VCO2}\right)^2 \quad (3)$$

Where X is the width of the coating and V CO_2 is the carbonation velocity.

The corrosion propagation time (tp) is determined according to equation (4).

$$tp = t\ construcción - ti \quad (4)$$

As reported by [8] for low-quality porous concretes, the carbonation velocity is V CO_2> 9 mm/year½, therefore, the corrosion onset is 11 years and the propagation time is 44 years to 55 years of exploitation of these buildings. In this sense, [19] states that the onset of cracking is 6 years for carbon steels and that the time required for the corrosion damage to spread from 2% - 12% is 16 years, therefore it is inferred that in 44 years the damage has spread much more.

Icorr and attack penetration (Px) are calculated by equations (5) and (6).

$$Icorr = (\text{Ø}o - \text{Ø}r)/tp \quad (5)$$

$$Px = (\text{Ø}o - \text{Ø}r)/2 \quad (6)$$

Table 3 presents these results, and it can be seen that in all cases, the Icorr is greater than 1.0 μA/cm². According to the contributions of [8], these values are in accordance with a high level of corrosion, as evidenced in the elements with pathological damage of the inspected buildings. It also specifies that, for the high corrosion level, the Icorr is between 1 to 10 μA/cm². On the other hand, [20] obtained values of up to 10 μA/cm² in carbonated wet concrete, although not saturated, as well as in concrete with medium chloride content.

Table 3. Icorr and Px in elements with pathological damage.

Øo (mm)	**Ør (mm)**	**Px mm**	**Icorr μA/cm²**	**Øo (mm)**	**Ør (mm)**	**Px mm**	**Icorr μA/cm²**
3	1.5	0.75	2.93	8	4	2.00	7.82
6	3.0	1.50	5.86	12	8	2.00	8.26

Taking into account the previous arguments, it is concluded that a 50% reduction in the diameter of the bars is possible, which represent a reduction from 55% to 75% of the cross-sectional area, for attack penetration values between 0.75 mm and 2.00 mm. Figure 2 shows the stains produced by the corrosion of the steel, in reddish-brown or orange tones, indicative of high levels of corrosion.

These results are also corroborated, when the evidence from Zhang et al. cited in [21], and research [22-26]. According to [23], a Px of 0.075 mm gives rise to cracks of around 0.3-0.4 mm in the concrete surface. Other investigations such as [25], indicate for reinforcement radius losses of 4% and 10% due to its corrosion, a maximum width of 0.1 mm and 1 mm, respectively. But according to the cracking pattern that exists in the elements inspected in this investigation, with generalized cracks and detachment of the concrete, the values of Px are evidently higher, as well as the percentage of reduction in the diameter of the reinforcement.

Research [22] shows the relationship between depth of attack and Icorr. They specify depth of attack values between 0.8 mm to 2.5 mm and for Icorr between 0.5 to 5 μA/cm². The previous results are not very different from those obtained in the present investigation.

Zhang et al. (1995, cited in [21]), in their tests carried out on carbonate elements, obtained Qcorr values of up to 67%, which represent reductions of the diameters of 42.6%. In [22] for 50 years after the corrosion began, with corrosion velocity of 5 μA/cm², it achieved average reductions of around 30% in the cross-sectional area of steel, although it obtained a 2% probability that the reductions of the cross-sectional area are greater than 80%, and therefore, there were reductions of approximately 45% of the diameter. Other authors such as [24] showed graphically for intervals between 30-60 years after the corrosion started, reductions in the useful surface of steel around 62.5%. In [26], 14% radio loss was obtained, but for a short period of 48-183 days.

In the present study and in the research [27], it is also observed that, in the elements with higher percentages of humidity, the most negative potential values and the highest values of Icorr are reached. That is, there are direct relationships between the Icorr and the corrosion potential. Although several investigations affirm that these parameters cannot be related, [8] asserts that direct relationships between them can be found in the same structure.

These elements with higher values of Icorr are the slabs, which belong to the most affected areas of the buildings, that is, the kitchen, bathroom, and service patio areas. Therefore, the Icorr is higher for the larger diameter steel bars, not only because the attack penetration increases as the crack openings are greater, but also because the highest moisture percentages were detected in these elements, which leads to more negative corrosion potentials with a correlation coefficient (R = -0.8964). Likewise, it is observed that as the velocity of the ultrasonic pulse increases, which is an indication of better quality of the concrete, the corrosion potentials become more positive, the correlation coefficient being (R = 0.9325). The correlations obtained are shown in figure 3. As the determination coefficients in each case are $R^2 = 0.8037$ and $R^2 = 0.8696$, in the range between 0 and 1, the estimated lines are representative for the data.

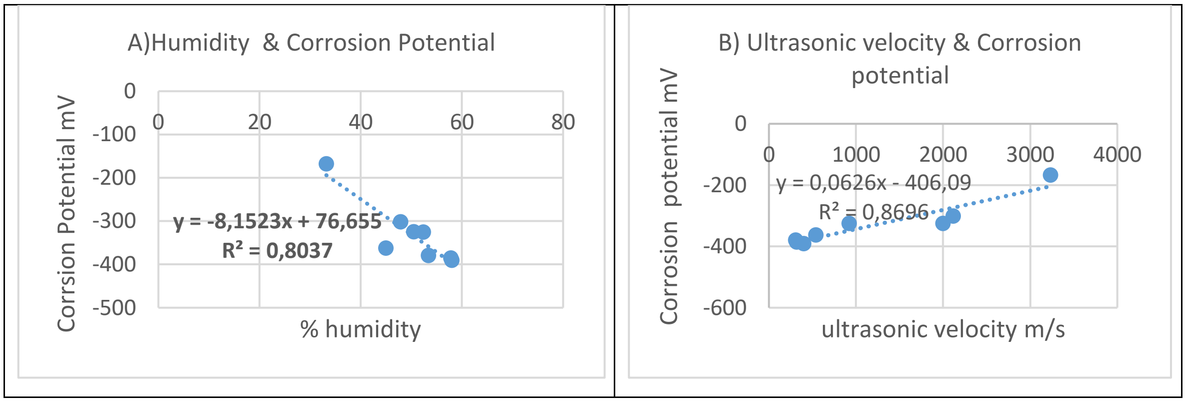


Fig. 3. Correlations between humidity, corrosion potential and ultrasonic velocity.

In figure 4A, it is shown how as the corrosion potentials increase (becoming more negative) in the elements with pathological damage, the Icorr increases. Since $R^2 = 0.4645$, there is a good correlation, which shows efficacy in obtaining the Icorr based on the measurement of corroded diameters. In figure 4B, the reduction (37.5%) of the yield stress of the steel bars can be seen, for a reduction from 55% to 75% of the cross-sectional area. These results do not differ much from those obtained in [28], where for section losses of 30-40%, yield stress reductions of 11% are obtained. Figure 5 also shows the decrease in yield stress for both corroded and non-corroded steels, as the bar diameters are larger.

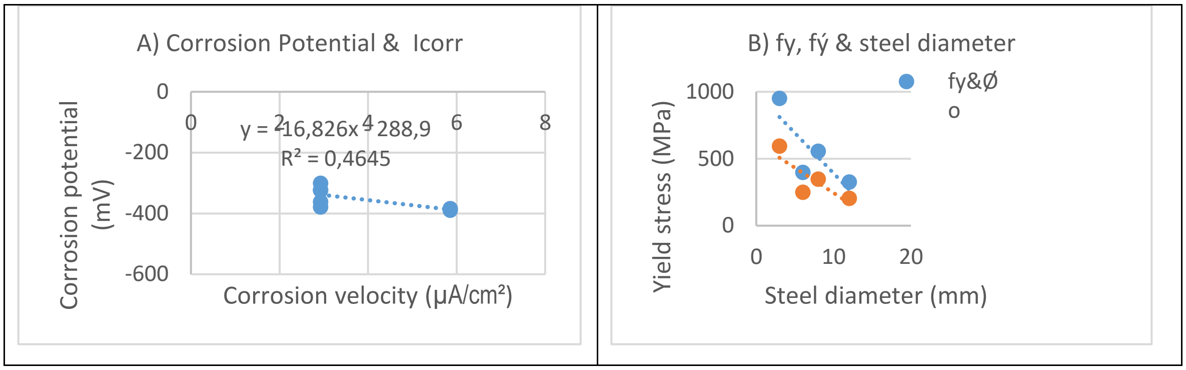


Fig. 4. Correlations between corrosion potential, corrosion rate, yield stress and rod diameter.

V. CONCLUSIONS

The reinforcement meshes in the prefabricated elements of the GSP system were formed both with steels of good ductility (diameters 9.5 and 12 mm) and with hard steels (diameters of 3, 6 and 8 mm). In the elements with pathological damage, a considerable reduction in the diameters of the corroded bars was obtained, in relation to the high levels of corrosion that exist due to the high percentages of humidity. This also affects an appreciable reduction (37.5%) in the yield stress of these bars. In the elements with higher percentages of humidity, the most negative potential values and the highest corrosion velocity values are reached.

AUTHORS' CONTRIBUTION

Yamila-Concepción Socarrás-Cordoví: Writing – original draft, Investigation, Formal analysis.

Liliana González-Díaz: Writing – review & editing, Supervision, Investigation.

Eduardo Álvarez-Deulofeu: Supervision, Investigation.

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