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Mechanical and Physical Study of Concrete Substitutes with Silica Powder Exposed in Simulated Aggressive Environment

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Abstract: The purpose of this research is to evaluate the performance of standardized cylindrical specimens in simulated exposure environments by immersing them in a 3% NaCl solution. The physical and mechanical evaluation was performed on reinforced cylindrical specimens of 30 cm high and 15 cm in diameter. The specimens are made of concrete with partial replacement of the cement by silica doses of 10% and 15%, with water cement ratios of 0.45 and 0.65 and a design strength of 250 kgf/cm². Settlement tests, porosity, capillary absorption and mechanical resistance were performed in a period of 5 months, and the influence of silica powder substitution in concrete mixtures on the standard mixture was analyzed. It was found that the mechanical strength increased compared to the design strength, with an a/c ratio of 0.45 and 0.65. Compared with the design strength, the mechanical strength of the substitute mixture reached an acceptable value. As for the porosity and capillary absorption tests, they were not satisfactory for any ration to a/c, probably due to lack of curing prior to exposure.

Key words: aggressive environment; substituted concrete; silica powder; compression resistance

1. Introduction

The sustainability of civil works seeks to balance the ecological, economic and social spheres in order to promote the development of society. As the quality of construction is intimately linked to the good use of resources and a good technical direction at all stages of construction, this circumstance has led to the search for improvements in both the constructive processes and the properties of the materials used in the structures, in order to prolong the service life of the project and ensure optimal performance. For this reason, this research aims to study in depth the causes, mechanisms and origins of the deterioration of contemporary construction, in order to prevent existing failures that may occur either in the design phase, during construction, or during use and maintenance.

It is for this reason that the study of alternative materials that offer to optimize concrete as the main material of the works has been developed in the Civil Engineering Department of the Lisandro Alvarado Central Western University (UCLA) for more than 15 years, which is framed in the research line registered in the CDCHT of the UCLA, 004-IC-2015 [1]. Several researches have been carried on the optimal dose of silica substitution in powder or sand, since this is an industrial waste material in Barquisimeto, which is known to improve the physical and mechanical properties for concrete. Based on this, the environmental variable was additionally incorporated in an accelerated and aggressive manner, in order to determine the suitability of this material for works located in natural environments with high chloride contents, which was achieved in a special degree work [2].

2. Development

One way to make contributions to materials technology is to test doses of alternative compounds obtained from waste in industrial sub-processes, incorporate them into the concrete mix, and expose them to accelerated environmental conditions so that it is possible to achieve the use of long-term durable non-traditional materials. In the case of aggressive chloride environments, the most significant effect is corrosion, which is a destructive electrochemical reaction of reinforcing steel that occurs in buildings exposed to the effects of the marine environment due to their location.

The impact of corrosion in the past was not very much considered at the time of the structure design, until the Fondonorma Technical Standard 4015-2012 Concrete Durability [3] appeared in the case of Venezuela. Therefore, it is increasingly necessary to investigate the problems caused by corrosion that may occur in these structures today and how to alleviate them. Therefore, the objective of this research focused on two parameters: one is physical parameter and the other is mechanical parameter, which are fundamental to guarantee that the concrete mix is durable, taking as a basis what has been determined in research developed by the authors [4], and what is framed by the aforementioned standard.

Silica dust is an industrial by-product, which comes from the disposal of silica sands from silicon metal or ferro silicon in electric arc furnaces. After being sieved in different sizes to be marketed, the residue remains in the form of powder that has no reuse in the industrial process. According to the American Concrete Institute (ACI) [5], this light to dark gray or sometimes bluish-greenish-gray powder also comes from the reduction of very pure quartz with mineral carbon in an electric arc furnace during the manufacture of silicon or ferro alloys.

Silicon dioxide, as an oxidizing vapor, rises from the oven to 2000℃, is cooled, condensed, and collected in a large cloth bag. After treatment, impurities are removed and their size is controlled, with over 95% being less than 1 μm. Micro silica is an additive that reacts in a humid environment with the calcium hydroxide resulting from cement hydration, which fills the empty spaces between the coarse aggregate and cement particles. This phenomenon is referred to as micro shrinking or micro filling. Similarly, due to its high content of silica, it has a chemical contribution and is a very active volcanic ash material in concrete [2].

The aggressive environment leads to a decrease in the durability of reinforced concrete It is a type of urban, marine, or industrial environment where the structural elements defined by physical, mechanical, and chemical interactions are exposed, which may lead to their degradation due to different structural behaviors considered in structural analysis [3]. In order to define the conditions in which the present research was carried out, the marine environment simulated through the semi-submerged exposure of cylindrical specimens in saline solution was considered, which guarantees aeration and humidification that accelerates the development process of some properties of the material.

In a technical report presented by [6], the corrosion behaviour of ASTM Type I (Ordinary Portland Cement, OPC) and ASTM Type V (Sulfate Resistant Cement, SRC) was studied by evaluating the protective performance of concrete by replacing 10% of the cement with microsilica and exposing the samples to 5% NaCl solution and seawater in the form of fog and by immersion. These mist tests were visually monitored and the conditions of the rebars were observed after 3, 9, 18 and 24 months of exposure and it was observed that the addition of microsilica appeared to be effective in reducing corrosion in the rebars, since it causes a drastic decrease in the permeability of chloride ion in OPC, as in concrete mixtures containing SRC.

On the other hand, it was observed that the steel for OPC cement mixed with microsilica was found to be more corroded in the immersion test compared to 5% NaCl solution in the environment. Likewise, it could be concluded that the mixture increases the compressive strength by 10% more in specimens with SRC cement compared to concrete containing OPC cement [6]. It is known that in order to build durable concrete structures in marine environments, it is necessary to have a very low permeability, in which the effects of replacing cement with fly ash or slag with and without silica fume are exposed [8].

In terms of the concrete strength properties, it was observed that the substitution helped to support the compressive strength at all ages, in hardened concrete tests up to 90 days of age. Therefore, when the combinations were used, the behaviour of the mixes at different ages was observed and it was concluded that replacing 40% of the slag with silica powder resulted in an increase in compressive strength, although this was slightly below the strength of the standard concrete in the long term. On the other hand, the replacement of 40% fly ash with silica powder was shown to exceed the strength of the standard concrete mix in both compressive and tensile tests after 7 days [6].

Similarly, the performance of Portland cement mixtures containing silica fume mixed with water-lime has been studied, including three mixtures: cement paste, cement mortar and concrete mix [9]. They monitored the development of compressive strength, the activity of silica fume in eight mixtures with percentages of 0%, 10%, 20% and 30% cement substitution, and the time taken for the steel bar to corrode.

Therefore, the research results indicate that by studying the compressive strength of two groups, the first group is water, and the second group is lime water, both of which contain the same proportion of silica. They observed how the compressive strength value of the first group mixture decreased compared to the second group. Among them, the lime water and 30% silica powder mix increased by 33.2% within 60 days of the control study. Similarly, they indicate that the combination of silica fume and lime water makes the microstructure more dense and permeable, resulting in a significant delay in the appearance of the first crack, thereby improving the corrosion resistance and low mass loss of the steel reinforcement [9].

In another research carried out, the objective was to evaluate the durability of a set of samples, consisting of 24 specimens (four for each type of mixture) prepared under a w/c ratio of 0.45 and 0.65 with substitution percentages of 0%, 10% and 15% for each w/c ratio and following the guidelines established in the Duracon Project [10]. The exposure and spraying time was 105 days, during which time periodic measurements of corrosion potentials were taken for the different coating thicknesses in order to determine the state of the reinforcing steel, electrical resistivity and corrosion rate.

They also evaluated the physical-mechanical properties of each concrete mix produced in the hardened state by means of compressive strength, porosity and capillary absorption tests. Once the results were analyzed, they determined that the mixes made with 10% and 15% substitution for both w/c ratios resulted in inadequate durability, recommending that further studies be carried out on mixes made with w/c ratios lower than 0.45 under the same substitution percentages, since they showed better performance when exposed to this type of environment [10].

Another contribution, whose purpose was the physical, mechanical and electrochemical evaluation of concrete made with partial replacement of cement by doses of silica powder at 10 and 15% with a water-cement ratio of 0.45 and 0.65, for a design strength of 250 kgf/cm^2, was carried out in a simulated marine environment with a 3% NaCl solution, where the specimens studied were semi-submerged in this solution. This was done in order to study the durability of the specimens [2].

With the results obtained, they determined that the silica powder was efficient in terms of decreasing the corrosion rate and electrical potential. On the other hand, an increase in resistance was obtained in the mixes with a water-cement ratio of 0.45. For mixtures with a water-cement ratio of 0.65, favorable values were found in terms of resistance; however, it did not have any beneficial effect on corrosion speed. None of the mixtures with silica powder studied in their work provided satisfactory results in terms of the evaluated physical tests of porosity and absorption.

3. Methodology

The purpose of this research work was to test standardized cylindrical specimens to evaluate their physical and mechanical properties in a simulated exposure environment by immersion in 3% NaCl solution. In reference to the research type in the present work, it is experimental, descriptive and field [11], since a collection of samples of fine and coarse aggregates was carried out in order to determine their characteristics and understand their nature.

Considering the need of the present study, the representative specimen selected was concrete mixes with partial substitution of cement by silica powder, subjecting it to different laboratory tests, to be used as an alternative material in construction. For the samples, 100% of the samples representing the study were taken and the water/cement ratio was determined; Subsequently, laboratory tests were conducted, and the distribution is shown in Table 1.

Table 1. Number of standard specimens and specimens with substitution for different w/c ratios

Mixtures	Pattern	Substitution 10%	Substitution 15%	Resistance test
0.45	4	4	4	9
0.65	4	4	4	9
Total of specimens	8	8	8	18

When the mix design was made according to the moisture content of the aggregates and the silica powder substitutions, the distribution of the parts was as shown in Table 2, in which the standard mix was that of concrete without silica powder additions as a cement substitute, i.e. the conventional concrete paste: water, sand, stone and cement.

Table 2. Dose of mixture

Element	250 kgf/cm²					
	pattern w/c ratio 0.45	w/c ratio 0.45 substitution 10%	w/c ratio 0.45 substitution 15%	pattern w/c ratio 0.65	w/c ratio 0.65 substitution 10%	w/c ratio 0.65 substitution 15%
Cement (kgf)	26.85	24.17	22.82	19.6	17.64	16.66
Water (kgf)	12.08	12.08	12.08	12.74	12.74	12.74
Fine aggregate (kgf)	46.98	46.98	46.98	49.42	49.42	49.42
Coarse aggregate (kgf)	46.98	46.98	46.98	49.42	49.42	49.42
Addition (ml)		282	282			
Silica (kgf)		2.68	4.03		1.96	2.94

3.1 Test tube processing

Standard cylindrical specimens of 15 cm in diameter by 30 cm high, and cylindrical specimens of 4" in diameter by 2" high were prepared. Table 3 shows the distribution of the sample by test and by type of mix.

Table 3. Distribution of the sample elaborated for physical and mechanical tests

Type of test tube	Mix pattern		Replacement of 10% of silica powder		Replacement of 15% of silica powder		Type of test
	w/c ratio 0.45	w/c ratio 0.65	w/c ratio 0.45	w/c ratio 0.65	w/c ratio 0.45	w/c ratio 0.65	
Cylindrical 30 × 15 cm	3	3	3	3	3	3	Compressive strength
Cylindrical 4" × 2"	4	4	4	4	4	4	Effective and apparent porosity

3.2 Test performed

The physical-mechanical tests performed were: a) slump, b) strength at 90 days, c) apparent porosity and d) effective porosity.

3.2.1 Test method to determine the porosity of concrete to measure its compactness

The testing of apparent porosity provides the percentage of voids in hardened concrete mixtures for research [12]. For this purpose, cylindrical specimens of dimensions 4" in diameter and 2" in height were prepared, considering the weight of the saturated specimens with dry surface and of the submerged specimens, which were recorded by means of a hydrostatic balance. Then, the samples were dried in the oven at a temperature of 105℃ until constant weight was obtained and recorded. Porosity was expressed as a percentage and calculated from the following mathematical expression:

$$\text{porosity } \% = \frac{\text{W saturated} - \text{W } 105℃}{\text{W saturated} - \text{W submerged}} \times 100 \qquad (1)$$

Evaluation criteria according to the "Manual of Inspection, Evaluation and Diagnosis of Corrosion in Reinforced Concrete Structures" [13]:

- Porosities ≤ 10% indicate good quality and compact concrete.
- Porosities between 10% and 15% indicate moderate quality concrete, but permeable and not suitable for aggressive environments.
- Porosities > 15% indicate a poor quality concrete, very permeable and unsuitable to protect the reinforcement.

3.2.2 Test method to determine the effective porosity based on capillary absorption

As specified in ASTM C642 [13], the overall objective of this test is to determine the water absorption capacity of concrete through the capillary action of concrete pores, using the same elements as previously used in pores. After drying them in the oven at a temperature of 105℃ until constant weight was obtained, they were cooled by drying. The test specimens were prepared by placing a thin layer of kerosene on their perimeter, to avoid the absorption of water by their sides. The initial weight was recorded, and then they were placed on a wet sponge inside a flat-bottomed cell, taking care that the water inside the cell reached up to 3.00 mm above the bottom of the test specimen, closing the container to avoid possible evaporation.

The recording of the weights was performed according to the "Manual of Inspection, Evaluation and Diagnosis of Corrosion in Reinforced Concrete Structures" [13] in time intervals 1/12, 1/6, 1/4, 1/2, 1, 2, 3, 4, 6, 24, 48 hours and so on until the constant weight was reached. From there, the other parameters can be determined to obtain the capillary absorption.

The coefficients were calculated based on the following equations:

$$m = \frac{t}{z^2}\left(\frac{s}{m^2}\right) \quad (2)$$

Where z represents the water penetration depth at time t.

$$k = \frac{(Wt - Wo)/A}{\sqrt{t}}\left(\frac{kg}{m^2 s^{\frac{1}{2}}}\right) \qquad \varepsilon e = \frac{k\sqrt{t}}{1000}\ (\%) \quad (3)$$

The coefficient can be evaluated as the slope of the linear region of the graph (Wt - Wo)/A as a function of $\sqrt{t}$. The coefficient m can be determined by calculating the time required for the water to rise to the top face of the specimen, i.e., when Z = H.

$$S = \frac{1}{\sqrt{t}}\left(\frac{mm}{h^{\frac{1}{2}}}\right) o\ (m/s^{1/2}) \quad (4)$$

3.3 Tests evaluation

The evaluation criteria according to the "Manual of Inspection, Evaluation and Diagnosis of Corrosion in Reinforced Concrete Structures" [12] are:

For coating thicknesses of 30 mm in severe environments, concrete with capillary absorption S ≤ 3 mm $/h^{\frac{1}{2}}(5.10^{-5}m/s^{1/2})$ is recommended; in less severe environments it can be up to 6 mm/ $h^{\frac{1}{2}}(10^{-4}m/s^{1/2})$; if the coating thickness is increased, the capillary absorption can be modified proportionally.

4. Analysis and Discussion of Results

4.1 Settlement

The workability test established by COVENIN 339:1994 [14], can be visualized in the results of Figure 1. For the w/c ratio of 0.65, the mixes with partial substitution of cement by 15% silica powder had a lower slump compared to the 10% substitution mixes.

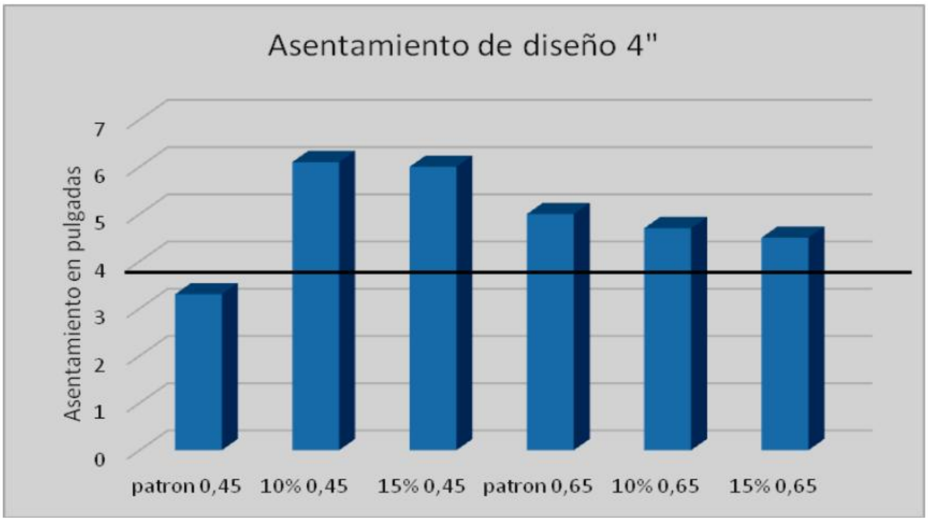

Figure 1. Average slump of standard and substituted specimens with both w/c ratios expressed in inches (kgf/cm²).

Similarly, in the specimens of the w/c ratio of 0.45, the same trend was maintained, i.e., as the percentage of dust increases, the workability decreases; this is due to the absorption by the silica. In addition, a fineness modulus of 3.30 was obtained, which indicates that it is a slightly coarse sand, which contributes to the low plasticity and workability of the mixture. For this reason, it was decided to use a super-plasticizing additive to improve the workability of those mixtures with a w/c ratio of 0.45 and partial substitution of cement for silica powder.

The super-plasticizer helped to make the mix much more fluid, resulting in settlements of more than 4" in the 10% and 15% replacement specimens. It should be noted that the percentage of aggregate additive was 1.05% of the weight of cement in each mix, according to the technical letter of the mix, which suggests a substitution percentage of 0.6 - 1.5% of the weight of the binder. Likewise, the addition of this super-plasticizer added a considerable additional cost that should be taken into account.

4.2 Compressive strength

The determination of the compressive strength of the concrete was carried out using a hydraulic universal press, by applying an axial load which produced the rupture of the specimens. The compression tests were carried out after 90 days of curing, thus allowing the silica to develop its bearing capacity. Figure 2 below shows the averaged results of the tests for a design strength of 250 kgf/cm² at 90 days, for all cases of substitution and standard mixes.

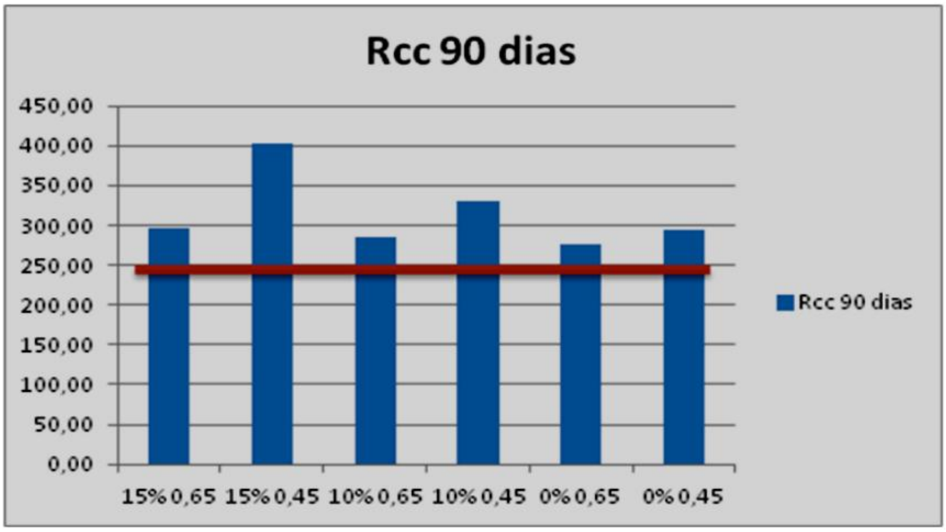

Figure 2. Average compressive strength of standard and substituted specimens, with w/c ratios (kgf/cm²).

The results obtained for the compressive strength of the standard mixes with a w/c ratio of 0.45 exceeded the design strength by 17.9%, which was established at 250 kgf/cm². Likewise, the standard mixes with w/c ratio of 0.65 exceeded the design strength by 10.7%. Therefore, according to COVENIN 338:02 "Methods for Preparation, Curing, and Compression Testing of Concrete Cylinders" [15], the test samples reflect acceptable results.

The compressive strength of the mixes with 10% of the cement weight replaced by silica powder and with a w/c ratio of 0.45 exceeded the design strength mentioned above by 32.5%. The mixture with 10% substitution and w/c ratio of 0.65 exceeded it by 13.7%. The compressive strength of the mixture with 15% substitution and w/c ratio of 0.65 exceeded the design strength by 18.36%, while it is specified that the mixture with 15% substitution and w/c ratio of 0.45 exceeded the design strength by 60.8%. As mentioned above, the design strength is set at 250 kgf/cm^2, greatly improving 401.91 kgf/cm^2, thus becoming high-strength concrete. In fact, it was determined that as the percentage of substitution increases from 10% to 15%, so does the mechanical resistance of the concrete.

4.3 Apparent porosity

The results of apparent or total porosity showed a concrete of inadequate durability for all specimens with w/c ratio 0.65 and standard w/c ratio 0.45. For the specimens produced with a w/c ratio of 0.45, replaced by 10% and 15%, a moderate quality concrete is observed according to reference [12]. For the first w/c ratio 0.45, a percentage of 14% was obtained, and for the second ratio it was 15%. It should be noted that the specimens for the test were not cured, since the aim was to recreate the most unfavorable and real conditions in Venezuelan constructions (see Figure 3).

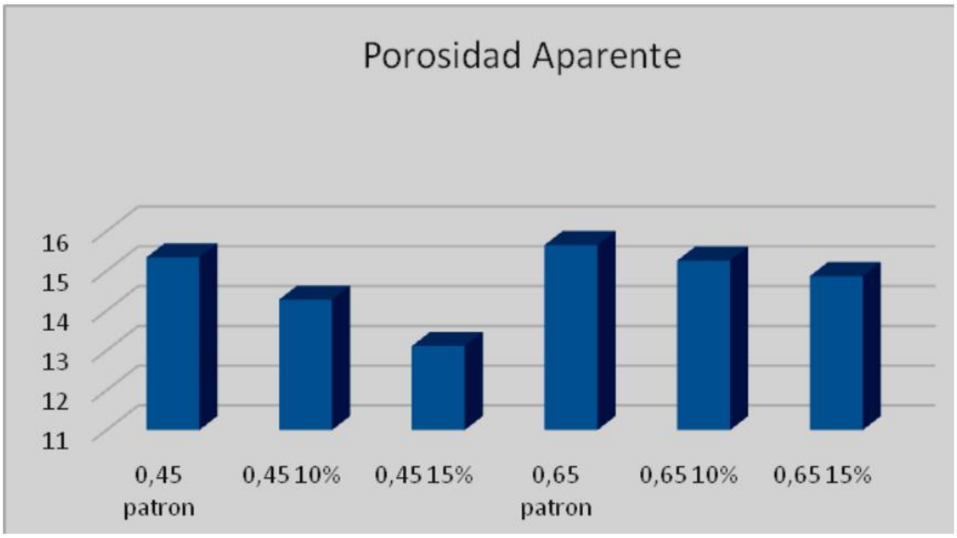

Figure 3. Average apparent porosity of standard and substituted specimens and with both w/c ratios.

4.4 Effective porosity

Figure 4 shows the effective porosity results, which show inadequate concrete durability for both w/c ratios. For the first w/c ratio 0.65, an average percentage of 18% was obtained, which is higher by an order of magnitude than the specimens of the second w/c ratio 0.45, which was 16.8%.

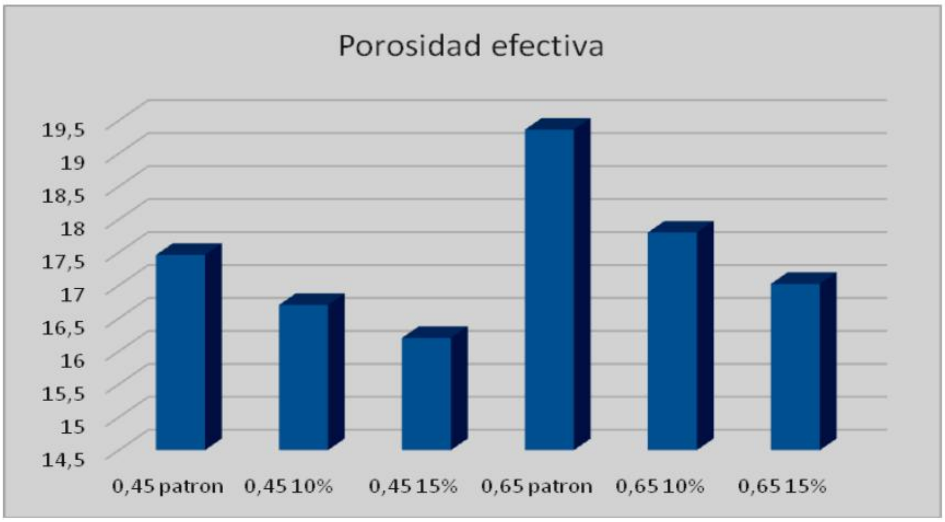

Figure 4. Average effective porosity of the standard and substituted specimens and with both w/c ratios.

Like the capillary absorption results, for specimens with an average w/c ratio of 0.65 at 4.89^{-4} $m/s^{1/2}$ and 0.45 at 1.66^{-4} $m/s^{1/2}$, the results indicate that the durability of concrete is insufficient according to the provisions of references [12] and [14], as it is recommended to use concrete with capillary absorption of S <= 3 mm/h² (5.10^{-5} $m/s^{1/2}$) for coating thickness of 30.00 mm in severe environments, but it is necessary to point out that the specimens studied have not been cured.

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6. Conclusion

The compressive strength results of the specimens with substitution obtained higher values compared to the standard specimens. Likewise, the strength values of the specimens with substituted w/c ratio 0.45 were the highest values achieved in the experiment, with an increase in strength of up to 60.8% with respect to the design strength, thus becoming a high-strength concrete with an average value of 401 kgf/cm².

Regarding the apparent porosity, it was found that as the percentage of silicon powder replacing cement increases, its value decreases. However, according to durability standards, it is still not suitable in all cases. The capillary absorption value and effective porosity value both decrease with the increase in the percentage of replacing cement with silicon powder, but due to the durability not meeting the required parameters, the replacement did not contribute to this. As for the workability of the mixture, plasticizing additives do indeed lead to this improvement in performance, as without such additives, the mixture would be very dry and difficult to mix. In this sense, its use allowed implementing the addition and working with it.

Conflicts of Interest

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

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