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Analysis of factors affecting certain testing methods to measure concrete's durability performance

Análisis de factores que afectan a algunos métodos de ensayo para la medida de las prestaciones de durabilidad del hormigón

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ABSTRACT

Certain concrete codes include, among other actions to ensure the durability of concrete structures, the measurement of different properties that can be an indirect index to evaluate the durability of concrete subjected to certain types of environments. This work aims to analyze the influence of several factors (nature of the aggregate, water/cement ratio, prior treatment), in the results obtained on concretes manufactured with aggregates of different nature commonly found in large areas of the Iberian Peninsula, when measuring two possible durability indicators: the depth of water penetration under pressure, used in Spanish legislation, and resistivity.

Keywords: durability; indirect durability indices; water penetration under pressure; resistivity.

RESUMEN

Algunos códigos de hormigón incluyen, entre otras medidas para asegurar la durabilidad de las estructuras de hormigón, la medida de determinadas propiedades que pueden ser un índice indirecto para evaluar la durabilidad del hormigón sometido a ciertos tipos de ambiente. Este trabajo tiene por objeto analizar la influencia de varios factores (naturaleza del árido, relación agua/cemento, tratamiento previo), en los resultados obtenidos sobre hormigones fabricados con áridos de diferente naturaleza, comunes en amplias zonas de la Península Ibérica, al medir dos posibles indicadores de durabilidad: la profundidad de penetración de agua bajo presión, empleada en la reglamentación española, y la resistividad.

Palabras clave: durabilidad; índices indirectos de durabilidad; penetración de agua bajo presión; resistividad.

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1. INTRODUCTION

Concrete is a material that exhibits excellent behavior over time. However, due to the sheer volume of reinforced concrete constructions, any durability issue in the material that requires repair, rehabilitation or replacement intervention of the affected elements entails major economic and social impact. The prevention of deterioration of concrete structures began to be considered in all concrete codes and regulations from the last decades of the 20th century, yet a fully satisfactory solution remains far off.

Most concrete codes establish prescriptive methods for the control of concrete durability (1), that regulate the type of components (cement type, aggregates, additions) that can be used and sets limiting values for concrete mixes (typically maximum water/cement ratio and minimum cement content). Although this approach has been successful up to a certain point so far, the main drawback is that the actual composition of the concrete delivered on site cannot be determined through testing, meaning the requirements can be verified in-situ only through documentary control.

To overcome this issue, certain codes have tried to introduce a performance-based specification for concrete durability. This approach is based in the measurement of relevant properties related to the transport properties of the concrete pore structure that can therefore be an indirect index of durability. Durability indicators used in practice might be physical parameters such as permeability to liquids or gases, water absorption, sorptivity, porosity or abrasion resistance, or chemical, physico-chemical and electro-chemical parameters such as diffusivity, conductivity, resistivity or migration coefficients of harmful species like chlorides.

Spanish regulatory codes have set the standard in terms of the treatment of concrete durability, both with prescriptive methods and through the designation of a durability index. The property designated by the Spanish government technical bodies for the indirect measurement of durability is the permeability to water determined by the measurement of the depth of penetration of water under pressure.

The test for determining this property on hardened concrete was standardized by the European Committee for Standardization (2) in 2001. The test is based on applying water at a pressure of 500 kPa for 72 hours on one of the sides of a specimen of hardened concrete. The specimen is then divided into two halves and the penetration depth of the water's front is measured. The standard specifies that, until the time of testing, the specimens must be cured while completely submerged in water.

This method was first used by Soroka at the beginning of the 1970s (3) in order to assess indirectly the durability of different concretes. Throughout the 1980s, it was adopted by different researchers to classify the quality of concrete from the point of view of its durability (4-6) due to its apparent simplicity in terms of implementation and interpretation of results. Although the rationale for the method used by these authors was the same, there were differences in their procedures in the curing regime prior to the test (submerged in water, humid chamber) similarly in the number of pressure steps and the magnitude of the applied pressure.

With a view to reducing the variability introduced by the above-mentioned factors, the method was standardized for the first time in Germany in 1978 (7), and later included in an ISO standard (8). In Spain, the adoption of the method is mainly due to the work carried out by the *Centro de Estudios y Experimentación de Obras Públicas* (CEDEX) in the 1990s. The laboratory work carried out by this organization (9-11) resulted in the drafting of a Spanish standard in 1990 (12). This standard features significant differences vis-à-vis the current European version of the test: it was established that, 24 hours before the test, the specimens had to be dried in an oven at 50±5ºC; during the test, three pressure steps were applied (100 kPa for 48 hours, 300 kPa and 700 kPa for 24 hours each) instead of a single pressure step; and finally, in addition to the maximum water penetration depth, the average depth was also determined.

The Structural Concrete Instruction (EHE) issued in 1998 (13) passed new legislation in Spain that established the determination of the depth of water penetration according to (12) as an experimental verification of compliance with the durability requirements of minimum cement content and maximum water/cement ratio. This verification had to be carried out for concretes subjected to exposure classes with risk of chloride corrosion, chemical attack, freeze-thaw or abrasion. The limits considered sufficient to guarantee the impermeability of concrete were 50 mm for the maximum depth, and 30 mm for the average depth, for all the mentioned environments and obtained as the average of three specimens. For individual specimens, the maximum depth allowed is 65 mm and the average depth is 40 mm).

The EHE was replaced in 2008 by the Structural Concrete Instruction EHE-08 (14), and this in 2021 by the Structural Code (15). The Structural Code maintains the determination of the penetration depth as proof that the concrete has sufficient impermeability to guarantee its durability during the structure's service life. The verification must be carried out using the single pressure step of the current European standard, but the EHE-08 introduced the modification, maintained in the Structural Code that, prior to carrying out the test, the specimens must be subjected to a drying period of 72 hours in an oven at 50±5ºC. The limits are the same as in the previous EHE Instruction, applicable to the same types of environments, though updated to the exposure classes defined in the European standard EN 206 (16) (corrosion by marine chlorides in aerial or submerged elements, corrosion by non-marine chlorides, freeze-thaw, abrasion, and weak and moderate chemical attack), with the exception of elements situated in the tidal range, severe chemical attack or prestressed elements subjected to moderate chemical attack, for which the limits are established at 30 mm for the maximum depth determined as the average of three specimens and 20 mm for the average depth (40 mm and 27 mm for individual specimens, respectively).

Despite the method's relative simplicity, doubts have been cast surrounding it due to the high variability of test results (17), and the influence of a large number of factors on the results (18). In this sense, it seems clear that the previous treatment can have a significant bearing on the depth of the penetration fronts for the same type of concrete, since in addition to the mechanism of transport of water by permeability in a porous medium due to the pressure gradient, the previous drying established by the Structural Code can lead to an additional transport mechanism, namely capillarity, which should lead to greater water penetration and can contribute to variability. Another issue pointed out since the method was used for the first time is the difficulty to correctly visualize the penetration front, especially in specimens cured using total immersion in water. The foregoing is why it is believed that the previous treatment was introduced in order to ensure the correct visualization of the front once the specimen is divided into two halves.

Another durability indicator that could be used to measure the durability performance of concrete is resistivity (19). Electrical resistivity can be defined as the ratio between an applied voltage and the resulting electrical current circulating in a unit cell of a material. The resistivity of concrete mainly depends on its porosity, water content and the chemical species present in the pore solution. One of the first authors in developing a testing apparatus for the measuring of resistivity in solid materials was Wenner (20). This method uses a probe fitted with four electrodes and has been successfully applied for the assessment of the corrosion of steel (21). One of the advantages of the four-electrodes probe is its non-destructiveness, which makes it especially suitable for the evaluation of existing structures (22, 23).

A further method for the determination of resistivity in concrete consists in two electrode plates directly applied to a concrete specimen (24, 25). This test, known as the direct method, determines the bulk electrical resistivity of concrete, yielding fewer variable results than the four-electrodes test, thus meaning it is considered as the reference testing method for resistivity in concrete.

Standards for both test methods for the determination of resistivity in concrete have been issued in Spain (26, 27), and at the time of writing this article (end of 2021), a work item is underway in CEN for the publication of a European standard collecting the two methods. However, although several publications try to promote the use of electrical resistivity as a quality control tool (28), this technique is usually not included in the current concrete codes and regulations like the recently published Spanish Structural Code.

As stated before, resistivity is mainly influenced by the moisture content of concrete. As such, in order to successfully characterize the concrete pore network connectivity, resistivity measurement should be performed on completely water-saturated specimens. For this reason, both testing methods establish that resistivity must be measured on concrete specimens cured in water

This work aims to evaluate the influence of three factors, the nature of the aggregate, the water/cement ratio and the previous treatment (curing submerged in water or previous drying in an oven as per the Structural Code procedure), in the results of penetration of water under pressure obtained on concretes manufactured with aggregates of a granitic, limestone and siliceous nature, common materials for the manufacture of concrete in large areas of the Iberian Peninsula. This interest is due to the difficulties highlighted by manufacturers of concrete prepared in order to meet the requirement established in the previous Instruction EHE-08, requirements that have been transposed to the new Structural Code.

Alongside the above, to aid in the search for a possible alternative index that could be used with guarantee to control the durability requirements, the work tries to evaluate the influence of two factors, aggregate and water/cement ratio, on the measurement of resistivity on saturated specimens, since it makes little sense to determine this property on dried specimens.

2. METHODOLOGY

2.1. Materials

For the manufacture of the concrete used in this study, a cement resistant to sulfates with the addition of ground granulated blast-furnace slag was used, type III/A 42.5 N/SRC according to the Spanish standard UNE 80303-1 (29), from the company Cementos Tudela Veguín, S.A.

The aggregates were granitic, limestone and siliceous rocks, the first one being supplied by the company General de Hormigones, S.A., and the last two by Hanson Hispania. S.A. Table 1 lists the main physical characteristics of the aggregates, density and water absorption, determined following the UNE-EN 1097-6 standard (30).

Table 1. Physical properties of the aggregates used. Density and water absorption according to UNE-EN 1097-6.

Nature	Size	Density (g/cm^3)	Water absorption (%)
Granitic	0/4	2.65	0.09
	6/12	2.56	1.16
	12/20	2.58	1.20
Limestone	0/4	2.69	0.43
	6/11	2.69	0.38
	11/22	2.69	0.38
Siliceous	0/6	2.66	0.30
	6/20	2.64	0.57

In order to achieve a similar workability for each of the concrete batches (between 40 and 100 mm of slump measured with the Abram's cone according to the standard UNE-EN 12350-2 (31), which corresponds to the interval defined as 'soft' consistency in the Structural Code, including tolerances), the polyfunctional admixture ME 3850 was used, provided by BASF.

2.2. Experimental design

To appraise the factors influencing the depth of water penetration under pressure, an experimental design featuring three factors (aggregate, water/cement ratio and treatment prior to the test) was performed, with three repetitions per combination of factors, resulting in a total of N = 36 results of testing.

For the water/cement ratio (w/c), two levels have been chosen, w/c = 0.5 and w/c = 0.7. The level w/c = 0.5 corresponds to a concrete that meets the requirement of maximum allowed w/c, established for one of the most unfavorable classes of exposure defined in the Structural Code that require the verification of the penetration depth. Hence, it was assumed that they would yield results within the limits of the Structural Code for both cases involving prior treatment, since the limits have been stablished for the case of previous drying. This case should be more unfavorable and therefore should yield higher penetration depth values. The second level chosen, w/c = 0.7, would correspond to concrete that does not meet the requirements, and therefore in theory should give results outside the limits established by the Code, at least for the treatment by drying during the previous 72 hours. The w/c ratio declared in Table 2 is the effective w/c ratio, i.e., not considering the water absorbed by the aggregates. The Spanish Structural Code establishes the w/c ratio limits for the total water, including absorbed water. Thus, the use of the limits with the effective w/c ratio is more unfavorable, so the results of the water penetration depth in case that the total w/c ratio should have been used would be lower.

Therefore, two types of concrete were manufactured for each aggregate, with the same cement content of 300 kg/m^3, and two different w/c ratios. The choice of cement content was made to be consistent with the durability requirement of minimum content in the Structural Code for the most unfavorable environments, and which require the verification by the water penetration test, considering that the lower cement content would be the most unfavorable case, since there are ambient classes that require higher cement contents (325-350 kg/m^3). To maintain the cement contents in each of the formulas, in order to isolate this factor, the volume of the aggregates was adjusted so that the same proportions were mutually maintained in volume. The six nominal dosages used are listed in Table 2.

Regarding the treatment prior to the test, two levels have been compared: on the one hand, the one given in the UNE-EN 12390-8 standard, conservation of the test specimens under water at 20±2°C until the moment of the test; and on the other hand, after the curing in water for 28 days, drying prior to the test for 72 hours in a forced air ventilation oven at 50 ± 5ºC.

For the assessment of resistivity, only two factors, aggregate and w/c, are analyzed. Only limestone and siliceous aggregates were considered, since the resistivity measurement equipment wasn't available when the granitic batches were manufactured. Since one reading over a concrete specimen is considered as an individual result, a total of N = 42 results of testing were obtained.

To comply with the number of tests provided for in the experimental design, a total of 18 batches were manufactured with the components described previously, 3 batches for each of the mixtures in Table 2. For each batch, 7 cylindrical specimens measuring Ø15x30 cm and 2 cylindrical specimens measuring Ø10x 20 cm, in line with the UNE-EN 12390-2 standard (32), were manufactured. All the specimens were kept for at least 28 days immersed in water at 20±2ºC. After the curing period, resistivity was measured according to the standard UNE 83988-1 on the seven Ø15x30 cm specimens per batch at the age of 28 days in saturated conditions.

Three Ø15x30 cm specimens from each batch were directly subjected to the test of water penetration under pressure according to the standard UNE-EN 12390-8. Three other Ø15x30 cm specimens were subjected to the drying stipulated in the Structural Code (72 hours in an oven at 50 ± 5ºC). One Ø15x30 cm was stored as reserve. For each test, the maximum and average depth of penetration of water under pressure were determined as the average of the three specimens.

The two Ø10x20 cm specimens were tested under compression according to the standard UNE-EN 12390-3 (33), at 28 days of age.

3. RESULTS AND DISCUSSION

3.1. Compressive strength

Table 3 displays the compressive strength results at the age of 28 days obtained on the two Ø10x20 cm cylindrical test specimens, for each of the 6 mixes by type of aggregate. The results are consistent with what expected forecasts, that is, an appreciable decrease in compressive strength when increasing the water/cement ratio from 0.5 to 0.7 (34%, 43% and 37% drop for granitic, limestone and siliceous aggregates respectively).

3.2. Water penetration depth

Figure 1 shows the box-and-whisker plots of the results obtained for the maximum and mean depth of water penetration. It is striking that the penetration, obtained as the average of three specimens for each of the combinations of factors, is in all cases below the limits established in the Spanish Structural Code for mass or reinforced concrete elements. This fact, which would be expected in concrete with a w/c ratio = 0.5, is

Table 2. Concrete nominal dosages.

Component	w/c = 0.5	w/c = 0.7	w/c = 0.5	w/c = 0.7	w/c = 0.5	w/c = 0.7
	kg/m³					
CEM III/A 42,5 N/SR	300	300	300	300	300	300
Water	150	210	150	210	150	210
Granitic sand 0/4 (49%)	930	854	--	--	--	--
Granitic aggregate 6/12 (15%)	280	257	--	--	--	--
Granitic aggregate 12/20 (36%)	680	624	--	--	--	--
Limestone sand 0/4 (50%)	--	--	965	887	--	--
Limestone aggregate 6/11 (15%)	--	--	290	267	--	--
Limestone aggregate 11/22 (35%)	--	--	685	630	--	--
Siliceous sand 0/6 (51%)	--	--	--	--	990	911
Siliceous aggregate 11/22 (49%)	--	--	--	--	960	884

Table 3. Compressive strength at 28 days for each of the mixes, tested in line with UNE-EN 12390-3.

Water/cement ratio	Granite	Limestone	Siliceous
0.5	46.4	48.5	43.0 (*)
	46.9	55.5	40.7
	42.3	48.9	36.9
Mean	45.2	51.0	40.2
Std. Deviation	2.5	3.9	3.1
0.7	26,9	31,3	26,9
	33,8	27,9	29,5
	28,7	28,7	19,0
Mean	29.8	29.3	25.1
Std. Deviation	3.6	1.8	5.5

(*) Result of a single specimen due to an unsatisfactory failure

nevertheless contradictory with what is expected for concrete with a w/c ratio = 0.7, since the purpose of the test is precisely to detect concretes that do not comply with the composition limits established in the Structural Code for durability reasons. Regarding the individual specimens, only one of them (out of a total of 54 individual specimens with w/c = 0.7) resulted in a value outside the limits (granite aggregate, w/c = 0.7, oven-dry, with a maximum penetration depth of 75 mm). Another observation that emerges from Figure 1 is the overly low average penetration values obtained in concretes made with limestone and siliceous aggregates, for both w/c ratios.

As the literature (17) has pointed out, a large dispersion of the results is observed, mainly in relation to the maximum depth of penetration. This high dispersion is highly influenced by the presence of outlier values in individual specimens. Although they can be detected by any statistical analysis of outliers, it was decided by the authors to keep them in the calculation of the results, since no experimental reason was found to consider its rejection beyond the variability of the test itself. In general, the previous oven drying treatment increases the dispersion compared to the specimens that were stored submerged in water until the time of the test, although it is true that the drying treatment gives, as expected, values above the specimens only cured in water.

Tables 4 and 5 show the analysis of factorial variance (ANOVA) performed on the results obtained for penetration of water under pressure. It follows that the three factors composing the analysis, aggregate, water/cement ratio and previous preparation, are statistically significant, since the three factors present

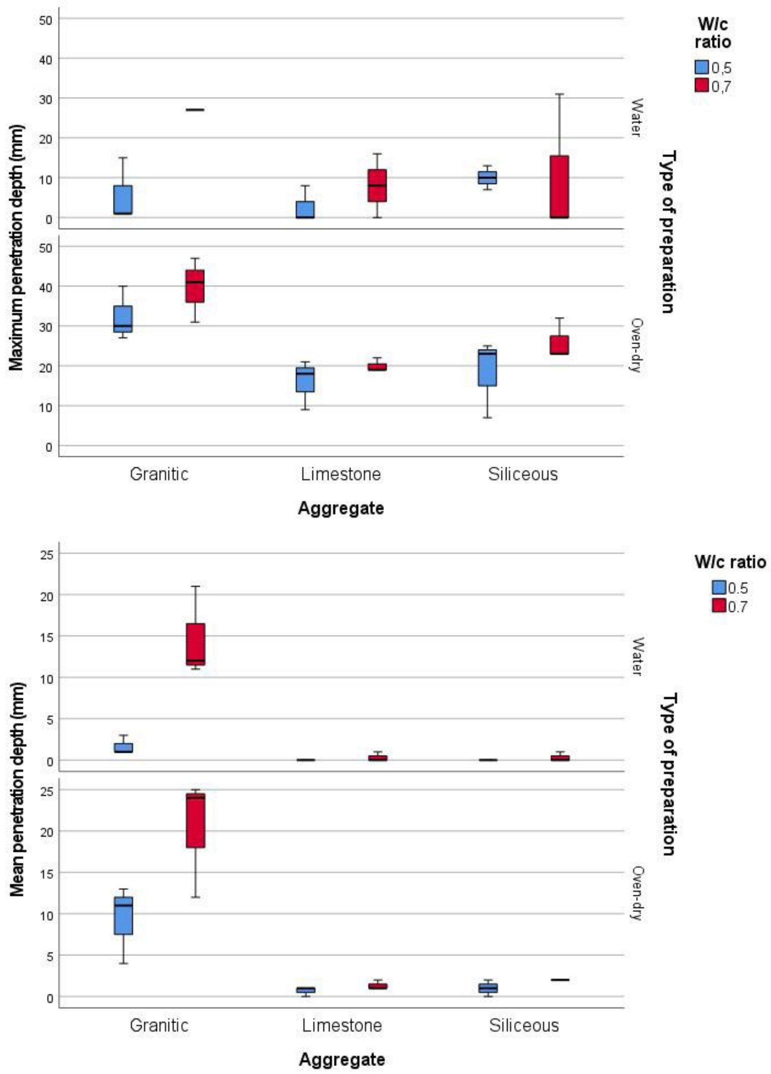

Figure 1. Box-and-whisker plots of the maximum (up) and mean (down) depth of water penetration (IBM® SPSS® Statistics v.25).

p-values lower than 0.05 (column "Sig.") for both measurements, maximum and mean penetration depth. This observation implies that the separate influence of the three factors is appreciable from a statistical perspective, which means that changes in the w/c ratio influence the results, regardless of the type of aggregate and the treatment. Figure 2 represents the mean values obtained for each factor, independently of the rest.

Regarding the type of aggregate, it is observed that the difference is mainly attributed to the use of granitic aggregates, since the values of maximum penetration are similar in concretes manufactured with siliceous and limestone aggregates. The average penetration value in these two cases is practically negligible, and only granite displays a considerable value.

An increase in both maximum and mean water penetration depth values is observed leading to an augmentation in the w/c ratio, which confirms the hypothesis by which this test was established as an instrument for controlling variations in the composition of concrete in terms of its water content established since the Instruction EHE; and vice versa: regardless of the aggregate and the w/c ratio, the previous drying produces variation in the results: in this case, the introduction of drying also increases the water penetration depth value. The observed statistical power for the three factors considered independently is greater than 0.80, representing a 95% confidence level.

With regard to the interaction between factors, the ANOVA indicates that there would not be a combined effect between paired factors (w/c ratio*preparation, aggregate*preparation or aggregate*w/c ratio) statistically significant for the case of maximum penetration depth, since F-values are reduced in all cases and the p-values are above 0.05. However, this result must be interpreted cautiously, since the observed power for the interaction term is low. For the mean penetration

Table 4. ANOVA table for the results obtained for the maximum water penetration depth under pressure (obtained using IBM® SPSS® Statistics v.25).

Test of Between-Subjects Effects. Dependent Variable: Maximum penetration depth						
Source	Type III sum of squares	Degrees of freedom	Mean square	F	Sig.	Observed power[b]
Corrected Model	4141.333[a]	9	460.148	7.085	.000	1.000
Intercept	11664.000	1	11664.000	179.588	.000	1.000
Aggregate	1322.000	2	661.000	10.177	.001	.975
W/c ratio	529.000	1	529.000	8.145	.008	.784
Preparation	1965.444	1	1965.444	30.261	.000	1.000
W/c ratio*Preparation	16.000	1	16.000	.246	.624	.077
Aggregate*Preparation	108.222	2	54.111	.833	.446	.177
Aggregate*W/c ratio	200.667	2	100.333	1.545	.232	.298
Error	1688.667	26	64.949			
Total	17494.000	36				
Corrected total	5830.000	35				
a. R squared = 0.710 (Adjusted R squared = 0.610) b. Computed using α = 0.05						

Table 5. ANOVA table for the results obtained for the mean water penetration depth under pressure (obtained using IBM® SPSS® Statistics v.25).

Test of Between-Subjects Effects. Dependent Variable: Mean penetration depth						
Source	Type III sum of squares	Degrees of freedom	Mean square	F	Sig.	Observed power[b]
Corrected Model	1507.139a	9	167.460	19.746	.000	1.000
Intercept	667.361	1	667.361	78.691	.000	1.000
Aggregate	932.056	2	466.028	54.951	.000	1.000
W/c ratio	173.361	1	173.361	20.442	.000	.992
Preparation	78.028	1	78.028	9.201	.005	.831
W/c ratio*Preparation	.250	1	.250	.029	.865	.053
Aggregate*Preparation	62.722	2	31.361	3.698	.039	.627
Aggregate*W/c ratio	260.722	2	130.361	15.371	.000	.998
Error	220.500	26	8.481			
Total	2395.000	36				
Corrected total	1727.639	35				
a, R squared = 0,872 (Adjusted R squared = 0.828) b. Computed using α = 0.05						

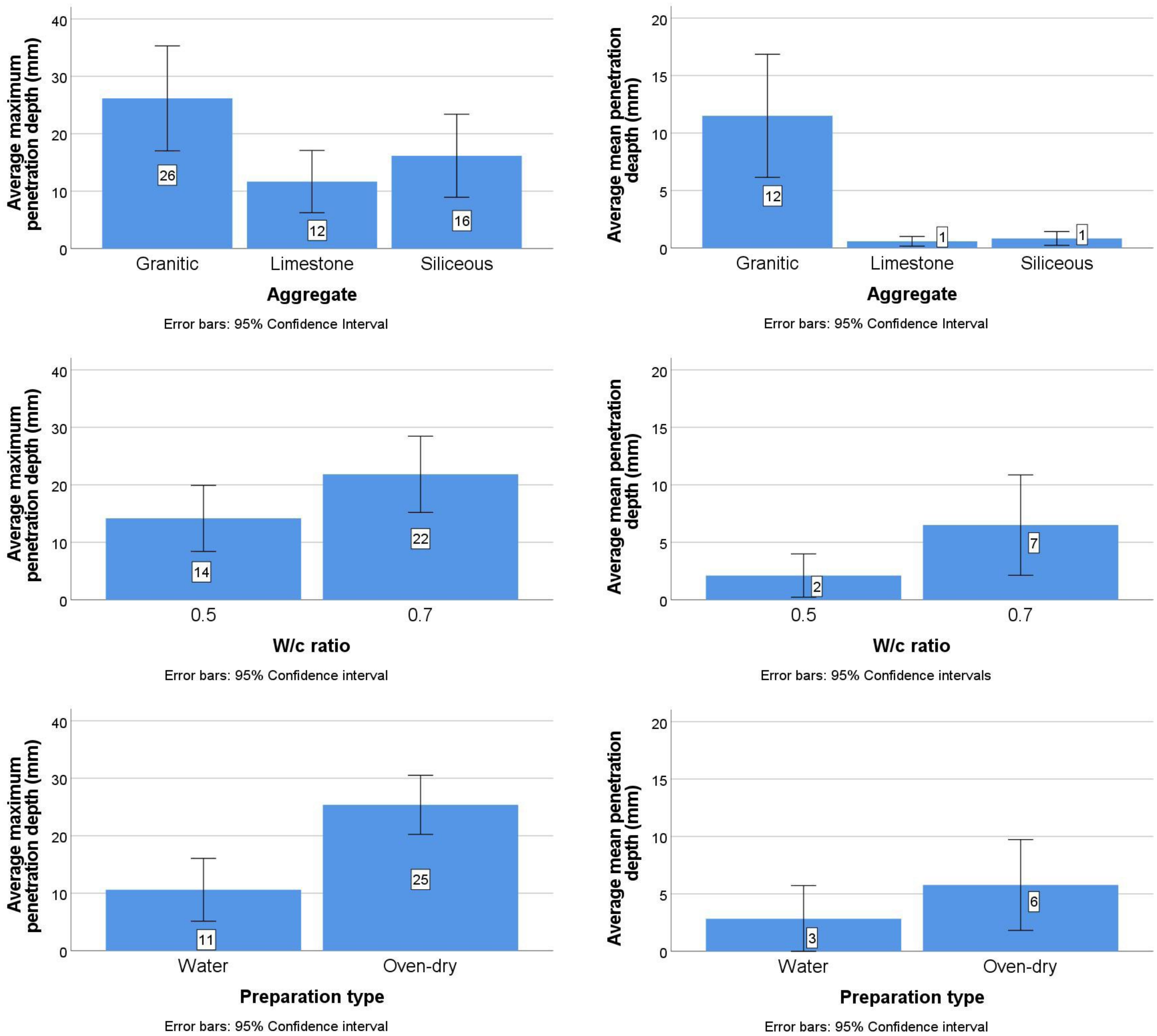

Figure 2. Bar graphs displaying the average maximum and mean depth of water penetration for each factor, independently of the rest: aggregate (upper), w/c ratio (middle) and previous preparation (lower) (IBM® SPSS® Statistics v.25).

depth, there would be an interaction when introducing the aggregate factor. Again, this interpretation must be viewed with caution, due in this case to the reduced value that this measure has for the case of limestone and siliceous aggregates, which introduces statistical significance, yet without a direct practical meaning.

3.3. Resistivity

Figure 3 shows the box-and-whisker plot of the results obtained for the resistivity at the age of 28 days. As expected, an increase in the w/c ratio decreases resistivity values, since a larger pore network entails a larger content of water in the concrete mass and therefore, since water is the main conductive medium, ions will move more easily.

With regard to water penetration, a widespread dispersion of results is also observed, especially for the case of siliceous aggregate. However, this variability does not confound the differences introduced by changes in the w/c ratio, as can also be verified through the results of the average values grouped by individual factors (Figure 4). Table 6 displays the ANOVA performed on the results obtained for resistivity at 28 days. In this case, only the w/c ratio is statistically significant (Sig. $<$ 0.05). This means that the test is able to detect differences between concretes with w/c ratios of 0.5 and 0.7. The aggregate factor is not significant, which can be due to the great variability showed, especially for the siliceous aggregates (hence the low observed statistical power for this factor). Yet, even with this level of variability, the resistivity seems to be able to detect the differences in the water content, which would make it adequate as an alternative test for the determination of a durability index for its control.

Regarding the interaction between factors, the ANOVA indicates that there exists interaction between the w/c ratio and the aggregate (F = 101.364; p-value = 0.00) and with a good statistical power (β = 1.00). This fact is corroborated through Figure 5, where it can be noticed that the lines do not follow a parallel path. The drop in resistivity is steeper in the case of the siliceous aggregate, which can be attributed to temperature variations or the different electrical properties of the aggregates.

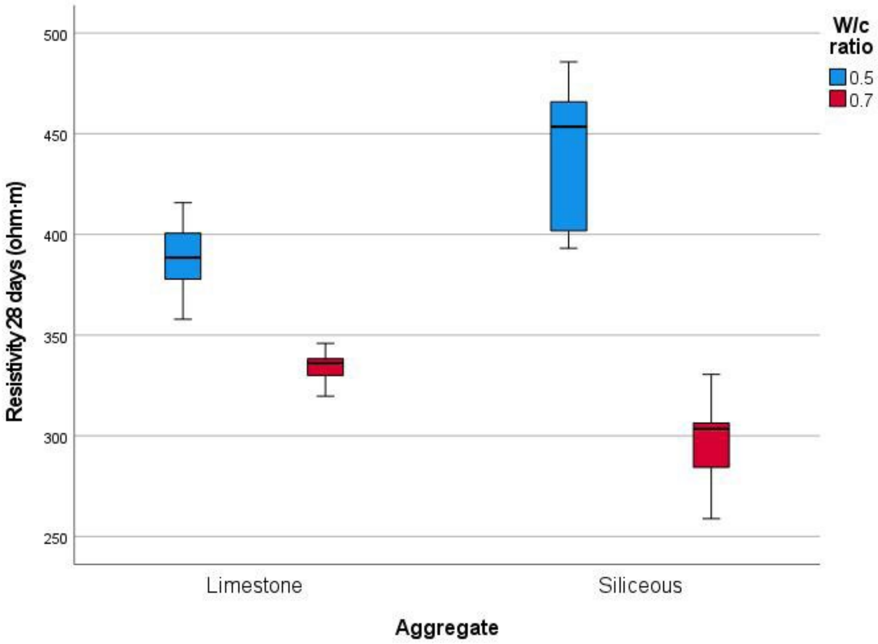

Figure 3. Box-and-whisker plot of the resistivity at 28 days (IBM® SPSS® Statistics v.25).

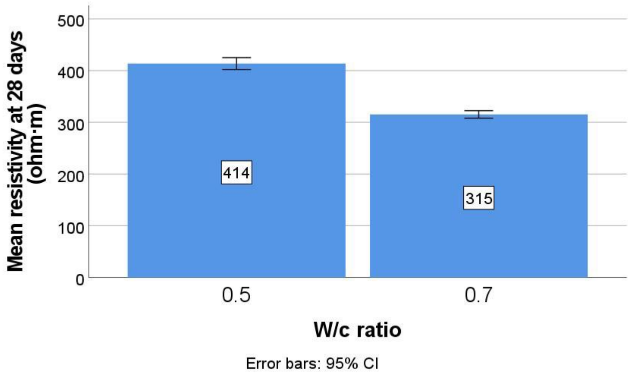

Figure 4. Bar graphs of the average resistivity for each factor, independently of the rest: w/c ratio (left) and aggregate (right) (IBM® SPSS® Statistics v.25).

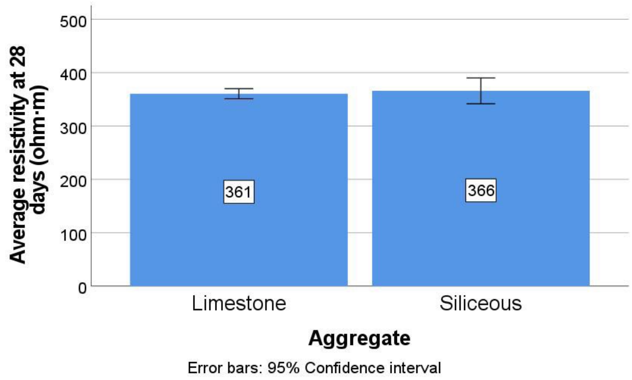

Figure 5. Estimated marginal averages for the resistivity at 28 days (IBM® SPSS® Statistics v.25).

Table 6. ANOVA table for the results obtained for the resistivity at 28 days (obtained using IBM® SPSS® Statistics v.25).

Test of Between-Subjects Effects. Dependent Variable: Resistivity at 28 days						
Source	**Type III sum of squares**	**Degrees of freedom**	**Mean square**	**F**	**Sig.**	**Observed power[b]**
Corrected Model	239551.960[a]	3	79850.653	198.106	.000	1.000
Intercept	10885312.600	1	10885312.600	27005.922	.000	1.000
W/c ratio	198090.102	1	198090.102	491.452	.000	1.000
Aggregate	871.183	1	871.183	2.161	.146	0.306
W/c ratio*Aggregate	40857.038	1	40857.038	101.364	.000	1.000
Error	31439.563	78	403.071			
Total	11091228.250	82				
Corrected total	270991.523	81				

a. R squared = 0.884 (Adjusted R squared = 0.880)
b. Computed using α = 0.05

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4. CONCLUSIONS

The water penetration test under pressure carried out on concretes manufactured from granitic, limestone and siliceous aggregates proved to be sensitive to changes both in the water/cement ratio and to the treatment by prior oven-drying established in the Spanish concrete codes. The results obtained on limestone and siliceous aggregates are similar, though not the values measured on granite aggregates, which present differences with respect to the other two types. The results showed a great dispersion, especially in the cases in which the specimens were previously dried according to the procedure stipulated in the Structural Code. Surprisingly, the test did not result in water penetration depth values outside the limits established in the Code, even when testing concretes with a water/cement ratio higher than the maximum water content limits established in the Code and when they were subjected to pre-drying.

The power observed in the test campaign does not allow to draw sufficiently conclusive statistically significant inferences regarding the effect of the interactions between various factors. Likewise, the difference in behavior observed between concretes with different types of aggregate (especially granitic) or the obtaining of penetration values below those expected in the regulation, suggests it is advisable to carry out future studies to bolster the results, increasing for example the power of the campaign by increasing the number of samples, extending it to a greater number of levels per factor or studying the influence of other factors such as the content of fines or the possible presence of entrapped air, among others.

Regarding resistivity, the results carried out on concretes manufactured from limestone and siliceous aggregates show that this test is also sensitive to changes in water/cement ratio. Results were similar for both types of aggregates. The variability of the results is also large, especially for siliceous aggregates, yet this variability does not confound the changes in water/cement ratio.

This study similarly stresses the danger of using indirect relationships between various properties of concrete such as compressive strength and indirect indexes of durability, correlated in occasions but without causality (34). This type of relationship can lead to incorrect deductions implying, for example, that concretes with higher compression strength are less permeable. In this work, granitic concrete showed higher compressive strength than siliceous concrete, while its water permeability was clearly higher.

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