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MEASUREMENT OF FRESH CONCRETE COMPONENTS USING ELECTRICAL IMPEDANCE

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Abstract.
The influence of concrete components on its the strength and durability, has been a recurring theme in the scientific community, where researchers have directed efforts to determine its composition in the preparation stage (fresh concrete). This measurement could improve the control of the concrete quality, impacting on the cost (without need to overestimation) and safety. The present work aims to correlate the electrical impedance components of the concrete mixture to its component's fractions (water to cement ratio – w/c; cement fraction – c and water fraction – w).
During these experiments, 34 different traits of concrete mixtures were evaluated in order to stablish the best frequencies for the measurement and correlations aiming to predict, from electrical impedance measurement of the concrete mixture, the real fractions of the concrete components. The correlations performed as follows: 82% of the collected data within the error of ±10% for the water to concrete (w/c) ratio, 91% within the error of ±10% for the cement fraction (c) and 97% within the error of ±10% for the water fraction (w).

Keywords: *multiphase instrumentation, electrical impedance, concrete resistance, concrete mix*

1. INTRODUCTION

Concrete is today one of the main components used in civil construction, but its use is not new. According to Andriolo (1984), there is evidence of the use of cement as a binder in Egyptian ruins some centuries BC, and the Greeks and Romans already used calcined limestone and later added lime, water and aggregates, giving shape to the first concretes in history. According to the author, the prototype of modern cement was obtained in 1845 by Isaac Charles Johnson. However, its use has been intensified by modern society in the last century and there are several justifications for its use, which include good resistance to compression, ease of molding (even in complex shapes) possibility of molding directly on site, ease of transport, and low-cost relative to other related material options.

The influence of concrete components on the strength and durability of concrete, in particular the amount of cement (*c*) and the amount of water (*w*), as well as the ratio between these two components (*w/c*), has been a recurring theme in the scientific community, where researchers have directed efforts to determine its composition in the preparation stage, that is, in fresh concrete.

One of the most important parameters for defining the type of concrete to be used is its elastic resistance, called fck (Feature Compression Known) - characteristic elastic resistance of concrete, expressed in megapascals (MPa), NBR 6118:2014 - which is standardized by NBR 5738 and NBR 5739, in Brazil. The fck value is directly dependent on the *w/c* (water to cement) ratio, obtained by the mass ratio between water and cement in the mixture. Not only does the *w/c* ratio define the fck of the concrete, this is a function of the combination of all the components of the concrete (in general: cement, fine aggregate, coarse aggregate, water and additives) in previously defined amounts and called mix. According to Robertson and Ley (2020), the *w/c* ratio is the most important parameter of concrete and has a direct impact on its mechanical properties. The authors mention, for example, that for a conventional concrete, for each increase of 0.01 in the *w/c* ratio, there is an impact of a reduction of 0.103 MPa in the compressive strength of the concrete and also a reduction of one year in the life expectancy of the structure. There is a wide variety of granulometry and types of aggregates on the market, in addition to different types of cement, and this whole combination will impact the strength (fck) and durability of the concrete. But, once the aggregate combination patterns are defined, which can be a particularity of each concrete, the strength of the concrete is directly defined by the *w/c* ratio. Another important parameter for specifying concrete is its workability. Concrete, for the most part, will be used in conjunction with steel reinforcement, which are responsible for ensuring the tensile strength of the structural element of the work. In this way, it is necessary and fundamental that the concrete completely surrounds the reinforcements, eliminating all empty spaces, which fatally compromise the resistance of the reinforced concrete structure. One of the most practical and simple ways to improve the workability of concrete is by adding water. However, adding water has a direct impact on the *w/c* ratio and, consequently, on the compressive strength of the concrete (fck), creating an antagonistic relationship that is difficult to control. One of the methods for controlling the workability of concrete is the Slump Test for Determination of the Consistency, standardized by NBR 16889 (in Brazil) and known in the market as the Slump Test.

Both the compressive strength test and the Slump Test are widely used in civil construction, but both have limitations. With regard to the Compressive Strength Test, its main limitation is the time required to obtain the final result of the fck which, according to the norm, is obtained only 28 days after molding the specimen. Although the result of this test can be predicted at shorter intervals, such as 24 hours, 3, 7 and 14 days, there is some discomfort in waiting until the 28th day to obtain the final result. The Slump Test, however, is highly dependent on the equipment preparation conditions, the location where the tests are performed and the executor's ability to execute and interpret the results, which may generate some insecurity depending on the value obtained. In addition, with the use of increasingly common and diversified additives, it is possible to easily manipulate the result of the Slump Test for the same trait, making it unfeasible to use this test as a reference for obtaining the *w/c* ratio.

The market also recognizes the need to have better control over these parameters, whether to improve the quality of concrete or even to optimize materials and reduce costs, but it lacks tools that can be applied in a simple and low-cost way in the field. Robertson and Ley (2020), Hou et al. (2022), Dey et al. (2020), Kim et al. (2022), Le et al. (2021), Khajehnouri et al., Park (2022) and Bello (2022) are examples of recent works that seek to determine *w/c*, *c* and *w*, from fresh mixture through different methods and algorithms, most involving electrical measurement of resistance and capacitance using artificial intelligence, neural network and machine learning.

In practice, in order to obtain a certain workability desired by the builder, it is common to add water or additives beyond what is foreseen in the mix, which can jeopardize the quality and safety of the work. In this way, seeking a way to perform this measurement of the *w/c* ratio and the mass fractions of water and cement from a fresh sample of concrete is totally relevant, and the purpose of this work was to perform it through the measurement of its electrical impedance properties.

2. METHODOLOGY

The main point of this this study was to measure the mix of concrete from its fresh mixture, before curing and setting. The methodology applied in the experiments was very empirical and, due to this, dependent of the operator experience and subjected to inaccurate results. In order to minimize these impacts over the results, several control conditions were determined, such as formalization of procedures, cards for each mix, definition of suitable places for each type of execution and preparation of the team. In terms of workplaces, three specifics were prepared in order to maintain the integrity of the materials, the correct preparation and separation of mixtures and the quality of measurements: 1. Storage and preparation of components; 2. Execution of kneading; 3. Measurement of electrical impedances.

2.1 Definition and provision of equipment and areas

The preparation of the kneading required specific equipment, as listed below:

- 1 Electric Concrete Mixer of 120 liters – this is the smallest volume mixer on the market, chosen to allow the preparation of mixtures in the smallest possible quantity;
- 1 Dryer with digital control with capacity of 85 liters and 3 ways to dispose of the material – necessary to dry the aggregates, mainly the fine aggregate;
- 1 Digital Scale with a capacity of 6 kg, being 0-3 kg x 1g and 3-6 kg x 2g – necessary to weigh components with less than 6 kg and guarantee a satisfactory level of error;
- 1 Digital Scale with a capacity of 30kg, being 0-15 kg x 5g and 15-30 Kg x 10g – necessary to weigh mass components from 6 to 30 kg and guarantee a satisfactory level of error;
- 1 Digital Scale with capacity of 0.50 kg and resolution of 0.01g.

Each component material of the concrete was stored in an individual container (box), duly identified and with a collection shell, in order to guarantee integrity, ease of location and practical collection of the same, as guided by NBR 7212.

To measure electrical impedances in broad frequency spectrums, the AGILENT 4294A Electrical Impedance Analyzer was used.

2.2 Definition of mixes

The mixes, in a simple way, are a combination of fine aggregates, coarse aggregates, binder, water and additive in predefined quantities. As fine aggregates, sand of natural origin or resulting from the crushing of stable rocks or even a mixture of both is normally used, whose grains, according to NBR 7211:2005, pass through the sieve with a mesh opening of 4.75 mm and are retained in the sieve with a mesh opening of 150 µm. As coarse aggregates, alluvial crushed stone or crushed stone from stable rocks is used, or a mixture of both whose grains, according to NBR 7211: 2005, pass through the sieve with a mesh opening of 75 mm and are retained in the sieve with a mesh opening of 4.75 mm. As a binder, Portland cement is one of the most common. The traits prepared for the experiment were based on market traits, whose composition was prepared by one of the project's collaborating companies. Usually, concrete makers prepare their mixes with focus, initially, on the mechanical compressive strength of the concrete (fck), and then about the workability (Slump Test), and then they reproduce them in laboratories to confirm the theoretical values that, after being confirmed, are documented as a standard recipe for the concrete maker.

Each mix to be prepared was described on a card, which contained information on the mass quantity of each component and spaces for noting the results of the Slump Test, temperature and relative humidity of the environment. The quantities of each component were calculated according to the specified volume for the mixture, which in the case of the present work was 20 liters. To define the ideal volume of each batch, practicality, ergonomics, safety and process quality were taken into account. Since these were laboratory tests, the intention was to produce the smallest possible volume of concrete, but using common and commercially available equipment to carry out the work, which in this case was a 120-liter electric mixer, the smallest on local market. The minimum volume suggested by the mixer manufacturer was 15 liters, while laboratory technicians and concrete mixers suggested values of 20 liters for the same mixer. Smaller (2 and 5 liters) and larger (30 liters) amounts were also tested. For the volumes of 2 and 5 liters, the result was non-homogeneous mixing, leaving a lot of material stuck to the wall of the mixer and forming lumps and, for the volume of 30 liters, although the result was satisfactory, the volume of mass generated made its final disposal even more difficult. Thus, considering the recommendations and tests, the value adopted was 20 liters.

The test matrix was the following: 4 consistency classes (S50, S100, S160, S220) and 6 *w/c* classes (0.45; 0.55; 0.65; 0.75; 0.85 and 0.95) were taken, in a total of 24 traits, which are close to the most common fck on the market: 20, 25, 30, 35 and 40 MPa. Additionally, 12 more mixes were prepared, all taking mix 9 (Class S100 and w/c==0.65) as a reference, however, varying the amount of additive (G1, G2, G3, G4), the amount of crushed stone (B1 and B2) and using other types of additives (C, D, E, F), in addition to mixes A1 and A2 that were carried out for time evaluation, with a total of 34 mixes.

In general, the materials were weighed as indicated in each mix card, based on the test matrix, then they were reserved in their respective individual buckets and then taken to the concrete mixer in the mixing preparation area. Each component was added respecting the sequence and times defined in the procedure for preparing concrete, as shown in Figure 1.

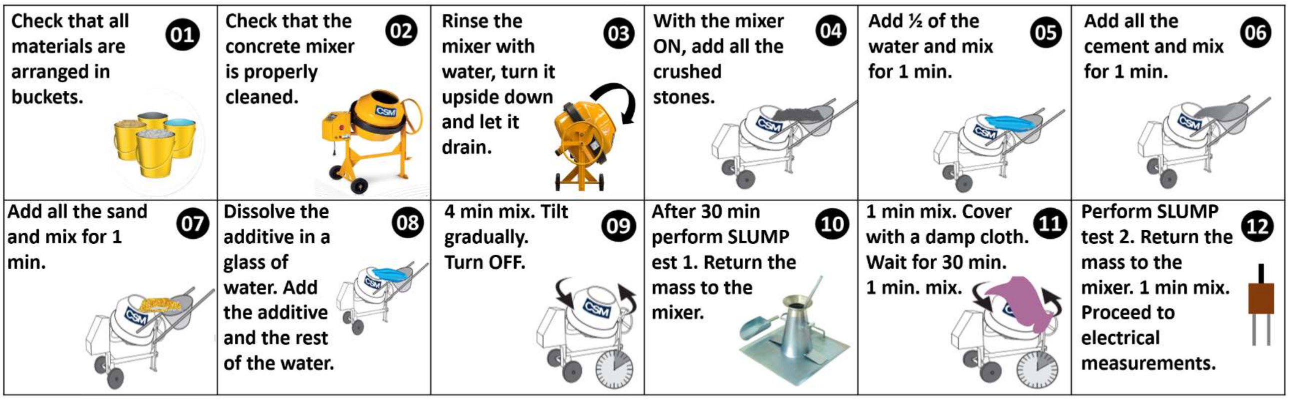

Figure 1. Concrete preparation procedure and measurement.

After collecting the sample from the mixer mix, it was taken to the laboratory for electrical measurement, where the electrical impedance analyzer and the probe were previously prepared, and finally, the measurements were made and the results recorded.

2.3 Components

The component materials of the concrete used in these tests were portland cement as binder, natural sand as fine aggregate, crushed stone as coarse aggregate, water from local supplier network and additive. In regularly prepared concrete on the market, there is a wide variation in the use of cement and aggregates, both because of its availability and financial goals, and because of the desired resistance (fck). In the case of these experiments, the components used are described in Table 1:

Table 1. Components used to prepare the experiments' kneadings.

Component	Supplier	Specification
Binder (ciment)	VC-ITAU DE MINAS CP II F-40	-
Crushed stone 0	PEDREIRA CARRASCOZA	4.8 < Ø grain < 9.5mm
Crushed stone 1	SANEN ENGENHARIA	9.5 < Ø grain < 19.0 mm
Fine Sand	CRS MINERAÇÃO	0.05 < Ø grain < 0.42 mm
Medium Média	PORTO UNIÃO	0.42 < Ø grain < 2.0 mm
Additive	GCP MIRASET 562	-
Water	REDE DE ABASTECIMENTO	-

All dry components were stored for more than 48 hours in 300-liter plastic boxes with lids, in order to guarantee their integrity and identification (NBR 7212). The water was collected in a 20-liter gallon and left for a minimum of 24 hours in order to equalize with the ambient temperature, which was always between 20 and 22 °C. The crushed stone was, for the most part, exposed to the sun with a visual and tactile evaluation of its drying. The sands were mostly dried in an oven at a temperature of 110 +/-5 °C for 24 hours (NBR 06457, 2016).

For weighing, three scales of different capacity and resolution were used, with the additive being weighed on a 500g scale, cement, medium sand and water were weighed on a 6 kg scale, and the other components on a 30 kg scale.

2.4 Sample Preparation and Measurement

Each fresh sample was left in a waiting time for 30 minutes, which, when added to the feeding, movements and handling times, reached close to 40 minutes. The interval of 40 to 60 minutes was adopted for carrying out the tests, which also helped to avoid the initial minutes of preparation of the mass and also the beginning of its setting, where a peak of heat happens, caused by an exothermic reaction of formation of hydrates, which occurs by the contact of cement with water. This peak lasts for a few minutes and rises again more slowly as soon as the mixture starts to set, that is, the beginning of solidification, and reaches a new peak, which marks the end of setting and the beginning of the hardening of the cement mixture.

Before starting the measurements of the samples, at least once a day, the calibration of the electrical impedance analyzer was checked following the procedure below:

1. Calibrate the equipment with the "Open" probe rods;
2. Calibrate the equipment with the "In Short" probe rods;
3. Calibrate the equipment with a standard resistor of 10 Ohms (1% Error) connected to the probe;
4. Check measurement with standard resistors R1=250 Ohms and R2=1 Ohm (1%Error) connected to the probe;
5. If the results of R1 and R2 are between 240 and 260 Ohms and 0.95 and 1 Ohm, respectively, proceed with the sample measurements, otherwise, repeat the procedure until R1 and R2 are within the specified range.

After preparing the batches of each mix, a sample of the mix was taken and sent to the electronics laboratory so that the measurements of the electrical impedances could be carried out, according to the following steps, which were described in Figure 2:

1. Collect the sample in a dedicated 16-liter bucket, plastic and without metal parts, and forward it to the measurement area;
2. Carry out a first initial compaction by lifting the bucket to a height of 3 cm and dropping it to the ground, repeating 3 times;
3. Insert the probe at once, in a random area and without marks from previous insertions, until covering the entire rod, but without covering the nylon cable, release the probe;
4. Perform a second compaction before measuring using a 0.6 kg rubber hammer, apply 10 blows around the bucket;
5. Reset the moving average of the impedance meter to zero and wait until it accumulates 5 new readings, making a new moving average of 5 measurements;
6. Remove the probe and return to step 3, repeating the procedure until completing 10 measurements in different positions in the bucket;
7. Clean the probe with water and dry it with a paper towel;
8. Return concrete to the external area to mold blocks and similar concrete artefacts.

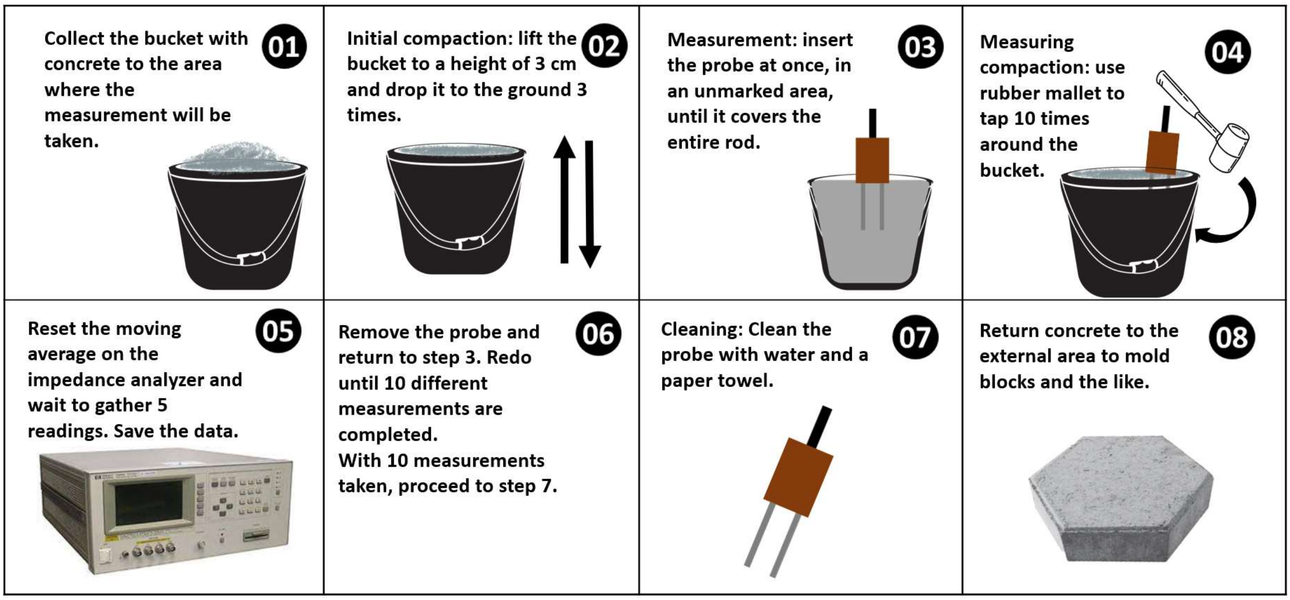

Figure 2. Procedure for measuring electrical impedance.

3. RESULTS

Through Figure 3, is possible to observe the result of measurements of the real (Resistance - R) and imaginary (Reactance - X) part of the electrical impedance of the mixes as a function of the signal excitation frequency. The existence of a proportional relationship between the composition of the trace and the value of the impedance is clear, since the lines are uniform from the beginning to the end of the frequency band, which varied from 40 Hz to 80 MHz and highlighted for 1 MHz in R and 10 MHz in X. Closed to110 MHz the lines joined and there was no longer any difference between the mixes.

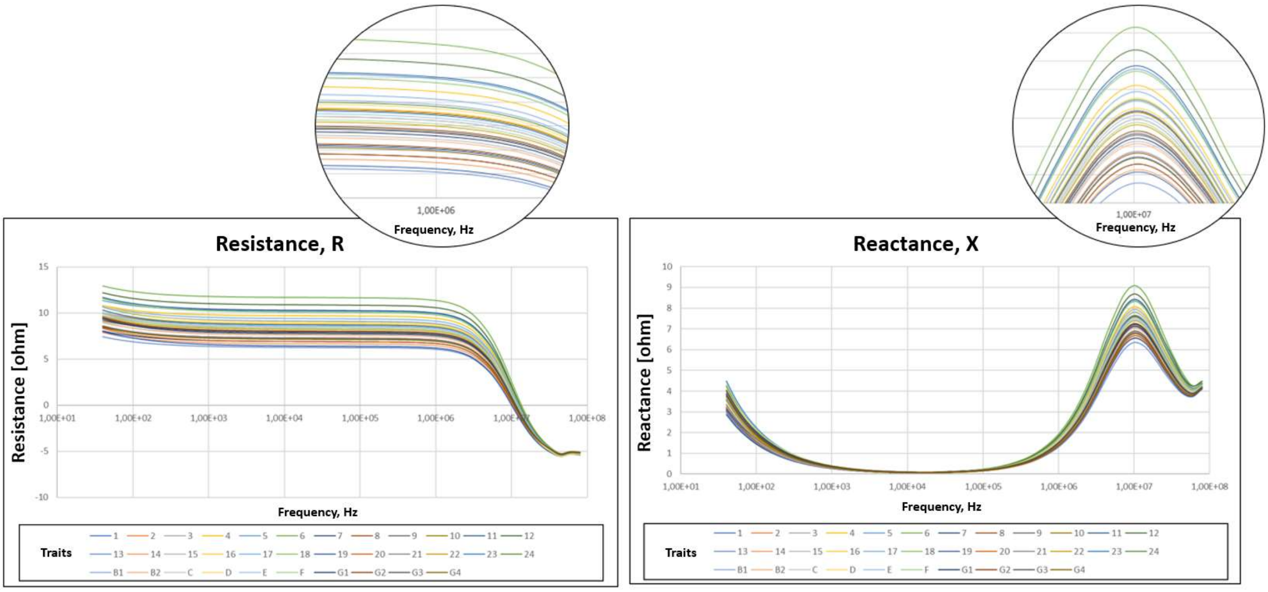

Figure 3. Result of measurements of electrical impedance components as a function of excitation frequencies.

Another way to verify the existence of proportionality between the mixes as a function of the *w/c* ratio (water mass/cement mass), cement fraction (*c*), water fraction (*w*) is through 3D graphics. In these graphs, it is possible to see the impact on R and X as a function of their variation, as shown in Figure 4.

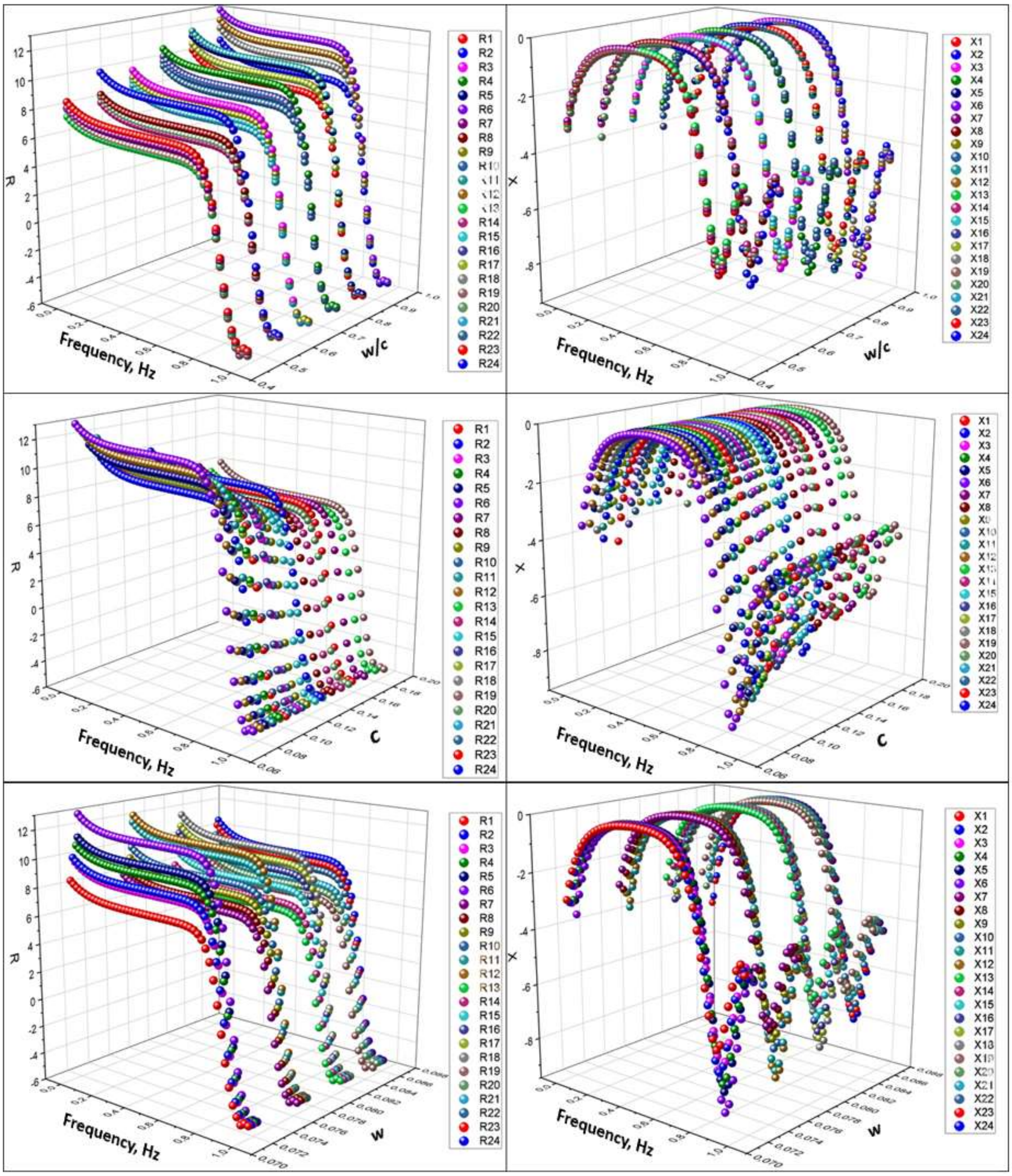

Figure 4. 3D charts of R and X as functions of *w/c*, *c* and *w*.

Based on these findings, it is necessary to define the best signal excitation frequencies to generate the mathematical model. Observing Figure 3, it is suggested that the best frequencies would be 1 MHz for R and 10 MHz for X and, through a series of simulations carried out with the MatLab software, three mathematical models were obtained for calculating *w/c*, *c* and *w* depending on the measurements of R and X, as shown in Figure 5.

Model to predict w/c

Frequency for Reactance X (x): $1.01 \times 10^7 Hz$
Frequency for Resistance R (y): $3.29 \times 10^7\ Hz$

Model:
- $f(x, y) = p_{00} + p_{10}x + p_{01}y + p_{11}xy + p_{02}y^2$

Coefficients (with 95% confidence bounds):
- p00 = -63.89 (-136, 8.202)
- p10 = 0.3384 (-1.948, 2.625)
- p01 = -25.85 (-52.35, 0.6461)
- p11 = 0.1341 (-0.3409, 0.609)
- p02 = -2.681 (-5.086, -0.2758)

Goodness of fit:
- SSE: 0.03009
- R-square: 0.9555
- Adjusted R-square: 0.9456
- RMSE: 0.04089

Model to predict c

Frequency for Reactance X (x): $1.01 \times 10^7\ Hz$

Model:
- $f(x) = a \times \exp(bx) + c$

Coefficients (with 95% confidence bounds):
- a = 37.15 (-43.26, 117.6)
- b = 0.9018 (0.5476, 1.256)
- c = 0.0668 (0.04759, 0.08602)

Goodness of fit:
- SSE: 0.001167
- R-square: 0.952
- Adjusted R-square: 0.9472
- RMSE: 0.007638

Model to predict w

Frequency for Reactance X (x): $1.35 \times 10^7\ Hz$
Frequency for Resistance R (y): $3.29 \times 10^7\ Hz$

Model:
- $f(x, y) = p_{00} + p_{10}x + p_{01}y + p_{11}xy + p_{02}y^2$

Coefficients (with 95% confidence bounds):
- p_{00} = -5.547 (-9.679, -1.414)
- p_{10} = -0.05738 (-0.1961, 0.08132)
- p_{01} = -2.157 (-3.671, -0.643)
- p_{11} = -0.01074 (-0.03955, 0.01808)
- p_{02} = -0.2071 (-0.344, -0.07016)

Goodness of fit:
- SSE: 9.743e-05
- R-square: 0.8316
- Adjusted R-square: 0.7942
- RMSE: 0.002326

Figure 5. Mathematical models obtained to obtain *w/c*, *c* and *w*.

Using the models in Figure 5 and applying the R and X values at the appropriate frequencies, it was possible to obtain the inverse result, that is, *w/c*, *c* and *w* from the measured R and X. The graph in Figure 6 shows the number of points within the +-10% error of the inverse model, first considering the 24 pure traces, then with the 10 additional mixes that were based on mix 9 but varying the crushed stone, the type of additive and the amount of additive. Considering the pure mixes, more than 90% of the points are within an error of 10% and with the 10 additional mixes the number of points within the +/- 10% becomes above 80%, that is, there is a loss of accuracy of the models. This loss can, initially, be explained by the fact that the alterations have an impact on the consistency of the concrete, verified by the results of the Slump Test, which influences the reading of the probe due to the greater or lesser contact with it.

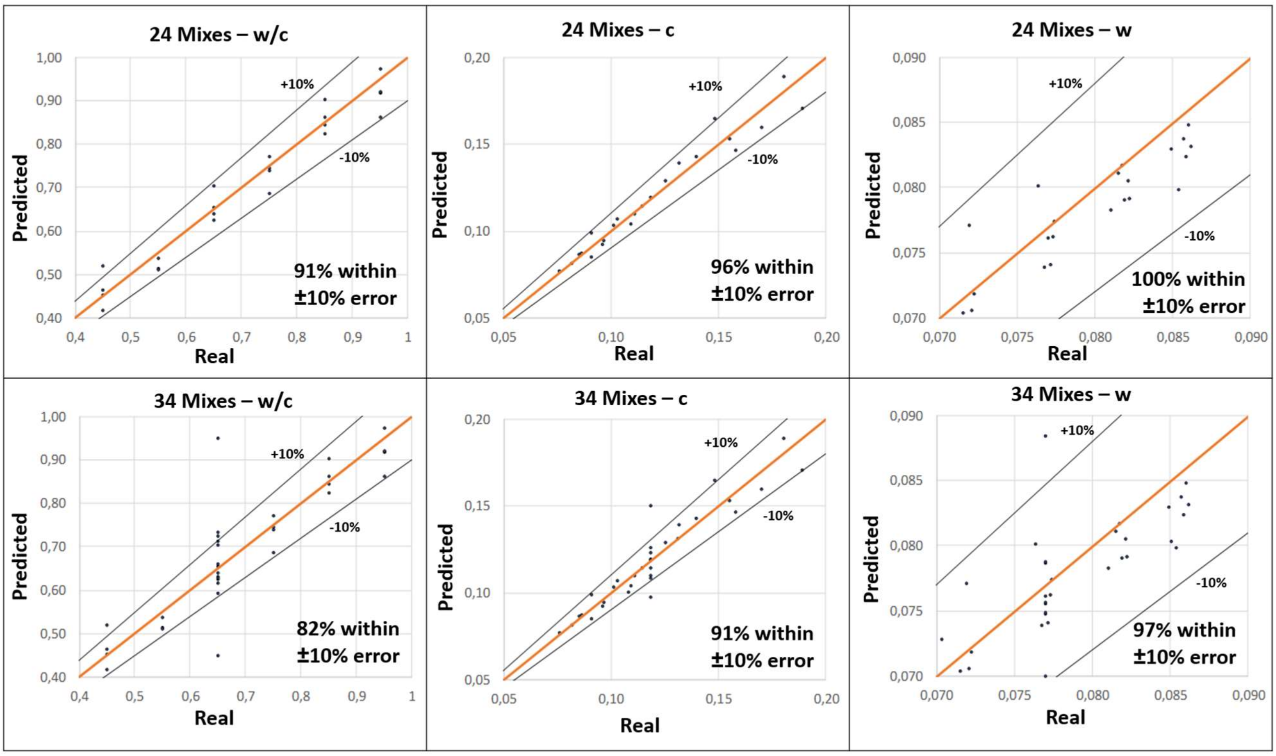

Figure 6. Error evaluation of the models applied inversely and within the range of ± 10%.

4. CONCLUSIONS

A methodology to measure the ratio of water to cement (*w/c*), cement fraction (*c*) and water fraction (*a*) in fresh concrete mixtures was developed. It is based on electrical impedance measurements.

Tests were performed to stablish the best frequencies for the measurement and correlations to predict (from electrical impedance measurement from the concrete mixture), the desired fractions of the concrete components.

For 34 different concrete mixtures, the correlations performed as follows: 82% of the collected data within the error of ±10% for the *w/c* ratio, 91% within the error of ±10% for the cement fraction (*c*) and 97% within the error of ±10% for the water fraction (*w*).

According some contacts stablished with the concrete market, a better accuracy is required for the results and, in order to improve it, new experiments will be performed from the learning acquired by the present methodology, that includes a higher range of frequency, a not intrusive probe, the same sample used for fck measurement and different data analyses, ideally using artificial intelligence models.

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6. RESPONSIBILITY NOTICE

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